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Hydrogen monitoring and measurement: Evidence report to support the development of LDAR and MCERTS standards

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We are the UK's National Metrology Institute (NMI), a world-leading centre of excellence that provides cutting-edge measurement science, engineering and technology that underpins prosperity and quality of life in the UK.

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Executive Summary

Hydrogen is an alternative conveyor of energy that could help decarbonise many areas of industry and could help countries meet their net zero emission ambitions by 2050. Although hydrogen is generally viewed as a clean conveyor of energy, emissions of hydrogen could negatively impact the environment by increasing the persistence of greenhouse gases in the upper atmosphere. Global hydrogen demand is increasing therefore reducing losses and minimising impact to the environment is becoming more relevant.

This report focuses on the development of Leak Detection and Repair (LDAR) and the Environment Agency's Monitoring Certification Scheme (MCERTS) standards whose aim is to eliminate, minimise and treat hydrogen emissions to the atmosphere as required by the Environment Agency's environmental permitting regime. This study has a focus on fugitive emissions from hydrogen production and its associated activities. LDAR schemes in the UK are either regulatory or voluntary schemes designed to identify and minimise fugitive emissions from leaking components as well as improving environmental performance and safety. The scheme will specify the type of sites to be inspected, focuses on fugitive emissions from components such as connectors, pressure relief devices etc. MCERTS is an Environment Agency (EA) certification scheme that sets out quality standards for environmental monitoring (air, water, land). It is an EA requirement for environmental permit holders. An MCERTS scheme provides a means for personnel, equipment and organisation(s) to demonstrate compliance with quality requirements for periodic surveillance of specific emissions to the environment.

Successful mitigation actions to reduce hydrogen emissions need reliable data, such data is underpinned by metrology. Therefore, metrology is an essential aspect of any monitoring scheme. Standard measurement-based monitoring methods are needed to provide the evidence data to successfully implement mitigation strategies such as a LDAR scheme. Currently, there are no standard methods for the monitoring of emissions available for use by industry and regulators.

The pre-Normative Hydrogen Release Assessment (NHyRA) European project (led by SNAM s.p.A. Italy and funded by the Clean Hydrogen Partnership) is currently developing

and validating methods for detecting and quantifying hydrogen emissions at component scale. Since these methods are based on an existing standard and use commercially available instruments, it is therefore conceivable that standard methods could be adopted within the next two to three years. Methods to detect and quantify emissions at larger spatial scales between approximately 1 m to several hundred meters (site spatial scale) rely on emerging techniques such as Raman spectroscopy or deploying networks of sensors capable of reliably monitoring hydrogen, therefore standardisation may require more pre-normative (i.e. research prior to standardisation) research and development.

To support the Environment agency in the development of policy and regulations related to the monitoring of fugitive hydrogen emissions at component level at hydrogen production plants the following key recommendations have been made: to obtain the necessary evidence data to design LDAR and MCERTS protocols that are fit for purpose and cost effective, to develop documentation and setup a working group between government, industry and the UK's NMI to help ensure the successful uptake, development and implementation of these schemes.

Evidence data on emissions and their characteristics, from different types of production sites and ranges of components are much needed to help support decisions that need to be made with regard to permitting, for example questions such as: what is the most cost effective LDAR survey frequency; are there specific component types to focus on; and what level of emission constitutes a leak? DESNZ funded measurement campaigns to measure fugitive hydrogen emissions have been conducted by NPL at research and industrial sites. It is recommended that further measurement campaigns are conducted to further build evidence data. It is important that evidence data includes quantification of emission rates since it can be difficult to represent emissions from concentration measurements alone. Examples of documentation are: on the use and testing of emerging techniques such as acoustic cameras and novel application of sensors, how to conduct a measurement or leak detection campaign, what are the best techniques to deploy and what data should be reported for a given monitoring need and MCERTS standards covering fugitive emissions of hydrogen. Engagement examples are: how industry plan to define and respond to leaks (covering purpose-built sites for hydrogen and adapted sites), the need to better understand how to monitor 'slip' from combustion processes, how best to get instruments to market, engagement with regard to the development of best practice guides, overcome barriers about product certification.

1. Introduction

This section begins with why monitoring and measuring hydrogen emissions is important; provides a brief definition of LDAR and MCERTS and their scope; followed by the objectives of this study and the rationale of how this study was conducted.

1.1 Why monitor hydrogen

Hydrogen is an alternative conveyor of energy and source of fuel that could help decarbonise many areas of industry, for example glass [1] and steel making [2] and could help countries meet their net zero emission ambitions by 2050. Global hydrogen demand reached more than 97 Mega tonnes (Mt) in 2023 [3], in order to meet net zero emissions by 2050, approximately 530 Mt will be needed to achieve this goal [4]. Although hydrogen is generally viewed as a clean conveyor of energy there are three aspects that could negatively impact the environment:

- Hydrogen emissions (e.g. from leaks) are an indirect greenhouse gas since it reacts with the hydroxyl (•OH) radical which increases the persistence of greenhouse gases such as methane in the atmosphere [5], therefore minimising hydrogen emissions to atmosphere are important.
- Emissions resulting from the supply of components and energy to produce hydrogen. For example, fugitive emissions from the upstream supply of Natural Gas (NG) to Steam Methane Reforming (SMR) hydrogen production plants.
- Emissions from within the hydrogen value chain (production to end use), examples are: carbon dioxide emissions (if not captured) from SMR and air pollution resulting from the combustion of hydrogen [6].

To date there is a high degree of uncertainty regarding the Global Warming Potential (GWP) of hydrogen which reflects the indirect radiative impacts of hydrogen via its effect on species such as methane, ozone and stratospheric water vapour. The GWP of hydrogen ranges from approximately 16 to 64 over a 20 year life time and approximately 3 to 18 over a 100 year lifetime [7–11] and there have been numerous studies to predict the amount of emissions to atmosphere and their impact, examples are cited in a previous report commissioned by the EA's Chief Scientist's Group (CSA) [12]; however these

studies are based on predictions of what the hydrogen economy will look like in the future rather than evidence from measurements.

Successful mitigation actions to reduce hydrogen emissions need reliable data, such data is underpinned by metrology. Therefore, metrology is an essential aspect of any monitoring scheme. Standard measurement-based monitoring methods are needed to provide the evidence data to successfully implement emissions these mitigation strategies such as a LDAR scheme. To date there are standard methods in place covering testing and use of systems that monitor hydrogen emissions for safety purposes, for example ISO 26142:2010 [13], EN 60079-29 [14–16] and ISO/TR 15916 [17]. However, to date, there are no standard methods for the monitoring of emissions that do not pose a safety risk i.e., emissions that generate lower concentrations than the Lower Explosive Limit (LEL), i.e. 4 %mol/mol and available for use by industry and regulators.

1.2 Definition of LDAR and MCERTS

This report focusses on the development of Leak Detection and Repair (LDAR) and Monitoring Certification Scheme (MCERTS) standards whose ultimate aim is to eliminate, minimise and treat hydrogen emissions to the atmosphere as required by the Environment Agency's environmental permitting regime.

LDAR schemes are regulatory or voluntary schemes designed to identify and minimise fugitive emissions from leaks as well as improving environmental performance and safety. The scheme will specify the type of sites to be inspected, focuses on fugitive emissions from components such as connectors, pressure relief devices etc.

MCERTS is an Environment Agency (EA) certification scheme that sets out quality standards for environmental monitoring (air, water, land). It is an EA requirement for environmental permit holders. An MCERTS scheme provides a means for personnel, equipment and organisation(s) to demonstrate compliance with quality requirements for periodic surveillance of specific emissions to the environment.

1.3 Objectives

This report supports the development of LDAR and MCERTS standards for the monitoring and measurement of hydrogen emissions. The objectives are:

- To identify gaps, current challenges and set requirements to facilitate the development of standards.
- Collate existing knowledge of current and emerging techniques and their suitability, scope, limitations and availability.
- Collate the information in a way to allow draft standards to be submitted to British Standards Institution (BSI) in the future.

As part of this project, a workshop was organised by NPL as held in December 2025 at the National Physical Laboratory between Government, Environment Agency (EA) and Department of Energy Security and Net Zero (DESNZ), and industry (consisting of instrument manufacturers, mobility, research, energy suppliers) and a UK Hydrogen trade association. The purpose of the workshop was to identify and discuss the key challenges and barriers for implementing LDAR and MCERTS. An overview and conclusions drawn from the workshop are described in Section 4.

1.4 Scope

This report will focus on the following areas: Leak detection and quantification at component level, use of snap-shot or periodic monitoring techniques, fugitive emissions from hydrogen production sites and the assumption that emissions contain hydrogen only, described in more detail as follows:

Leak detection and quantification at component level.

Figure 1 illustrates the different temporal and spatial measurement scales involved in monitoring a site. The x-axis represents the temporal scale from ‘snapshot’ to continuous measurement. Periodic could mean regular snapshots or a near continuous measurement but with gaps in coverage. The y-axis represents spatial scale: component (e.g., a flange), functional element (e.g., a storage tank), site and multiple sites clustered together; the scales provided are approximate. The scope of this work is indicated by the green area in

Figure 1. Component scale cover emissions of less than approximately 1 m spatial scale, for example leaks from valves.

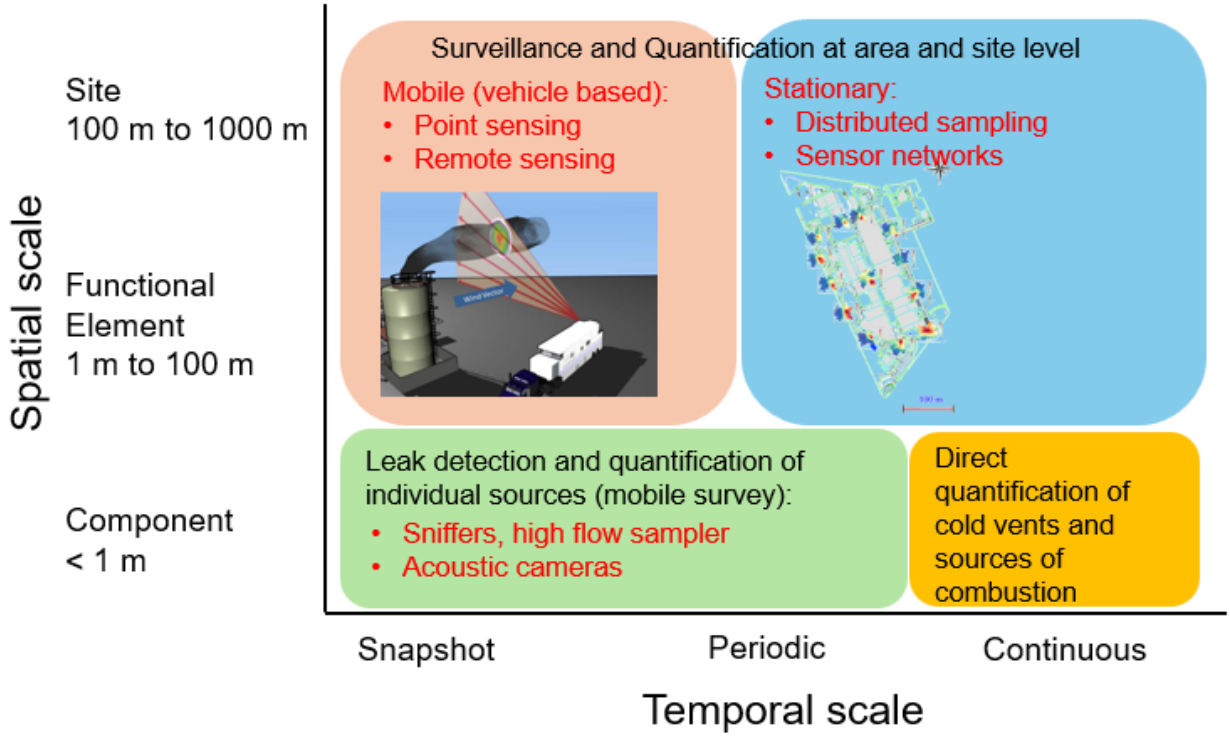

Figure 1. Spatial and temporal scales – hydrogen monitoring [18].

Detection of hydrogen emissions consists of the process of identifying the presence of hydrogen considered to be above some defined threshold that is above the detection limit of the monitoring method, by measuring a physical quantity (e.g. gas concentration, acoustic emission) relative to a background that infers the presence of a leak.

Quantification is typically represented as an emissions rate (mass per unit time) or leak rate (volume per unit time). This can be achieved, for example, by directly measuring gas concentration inside a sampling device using an internal pump and then combining that with a direct measure of sampling flow rate, using a model to represent flow or correlate a gas concentration with a set of predefined correlation tables. Alternatively, some techniques measure a quantity that infers the presence of a leak (e.g., acoustic intensity).

This report covers both aspects: detection and quantification. The implementation and prioritisation of a LDAR scheme will be dependent on the characteristics of the emissions and how they are affected by the environment. Since there are few data (based on

measurements of emissions) of real-world real sites, quantification will be an important aspect to build the necessary knowledge in order plan and implement LDAR schemes.

Snap-shot or periodic monitoring techniques

Techniques that involve mobile (human portable) survey, since instrumentation is commercially available (apart from the high flow sampler) and methods are currently being developed and validated using a standard from Natural Gas (NG) and (Non-Methane Volatile Organic Compound (NMVOC) sectors.

Fugitive hydrogen emissions from production facilities

Emissions from the hydrogen production section of the value chain. Figure 2 defines the different sections of the hydrogen value chain.

Figure 2. Hydrogen value chain

However, in principle the outcomes from this study could be applied to any part of the value chain and associated activities at production sites such as storage, vents and combustion. It is assumed that the gas composition within the value chain is pure hydrogen, but to provide brief commentary on blended gases (i.e. hydrogen enriched NG).

1.5 Related work

This report refers to and builds on the following related work with hydrogen monitoring development:

- A previous study (Net Zero: Hydrogen monitoring review) [12] commissioned by the EA's CSG to assess the different types of emission sources and monitoring techniques for hydrogen.
- The pre-Normative Hydrogen Release Assessment (NHyRA) project [19] (led by SNAM s.p.A. Italy and funded by the Clean Hydrogen Partnership) which is currently developing and validating methods for detecting and quantifying emissions at component scale. Test and validation activities are being led by NPL using the facilities described in Annex 1.
- Recent hydrogen measurement campaign's undertaken by NPL, funded by DESNZ.

1.6 Rationale

The following explains the rationale for the way in which this study was conducted. There are a wide range of commercially available instruments that can measure concentration of hydrogen, but there are no standard validated methods to apply these instruments to monitor emissions. Monitoring methods must be based on robust metrological principles so that data they provide can be trusted. A method is more than just an instrument and a manufacturer's instruction manual; there are critical elements that a method must have to ensure that the data it provides can be trusted so that the correct course of action can be taken to reduce emissions. These elements include: a sampling strategy (when and where to take measurements), a means to convert concentration into an emissions rate, personnel competencies and quality control and assurance procedures. Such a standard method could be used as part of a LDAR programme. A method should be validated against defined criteria (including performance) and periodically validated to provide assurance regarding its performance and competency of operators (an example is the Environment Agency's MCERTS scheme).

A framework concept based on a taxonomy that aims to provide a standard way of describing data, process and objects was developed for methane [20] and could be applied to hydrogen, refer to Figure 3. This concept should be used to choose or specify a method and highlight the technological or methodological gaps between what is needed and what is available. The choice of method or specification of a new method should be based on the monitoring needs and knowledge of the emission source. The monitoring need involves defining specific data reporting requirements (such as limit of detection, uncertainty etc) defined by having a clear understanding of the monitoring drivers (for example: regulations), purpose and monitoring objectives (for example to detect and then quantify hydrogen leaks from components). Knowledge of the emissions source includes its type (i.e. fugitive, vented or incomplete combustion), its emissions characteristics (e.g. gas composition), and its physical characteristics (e.g. size).

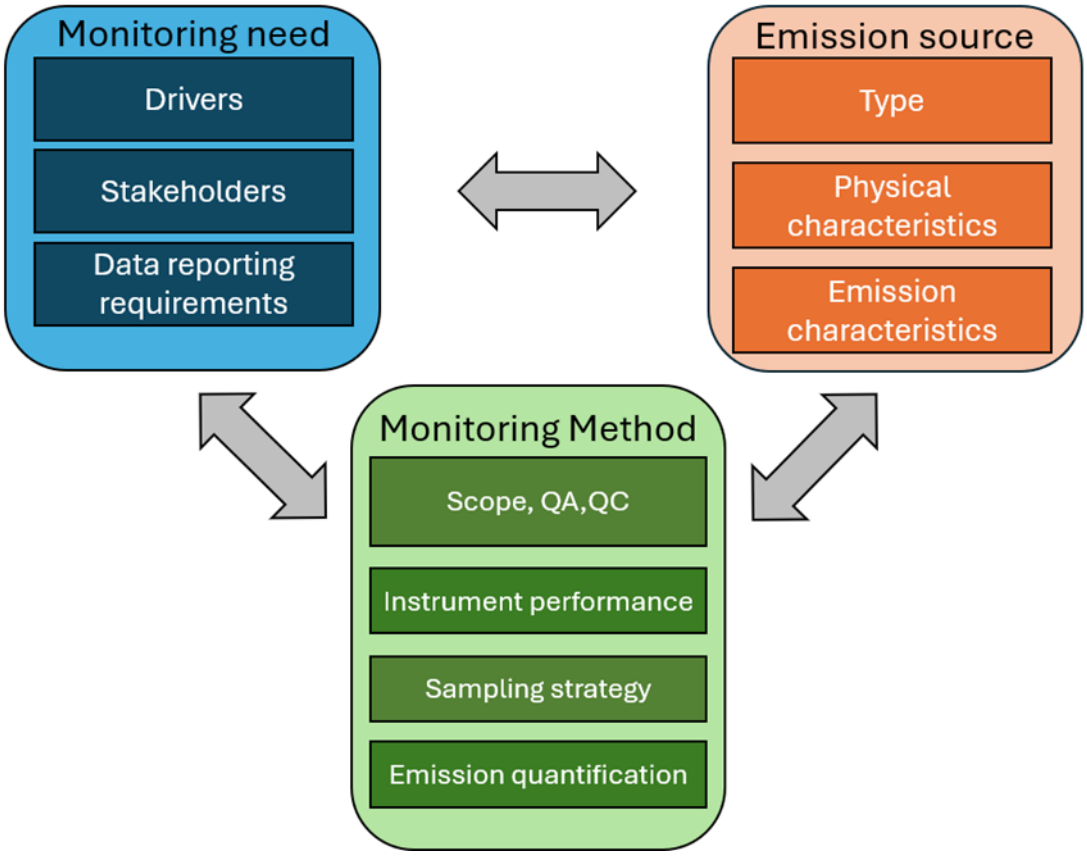

Figure 3. Monitoring needs, emissions source and monitoring methods [20].

This work used the taxonomy concept (understanding the monitoring needs and emissions sources to address the problem of defining methods). Section 2 provides an overview of the development of LDAR and MCERTS standards. Section 3 provides an overview and comparison of different techniques covering high and low Technical Readiness Level (TRL) for monitoring hydrogen that are within the scope of this work; also, a brief mention of techniques that are out of scope, but of interest (e.g. quantifying emissions from vents).

The methods being developed under NHyRA [21] are based on an existing standard (EN 15446 [22]) and the associated techniques use commercially available instruments (apart from the high flow sampler), it is therefore conceivable that standard methods currently used for Natural Gas, methane, NMVOCs could be adopted within the next two to three years [18]. Therefore, component level is a pragmatic focus for this work.

Methods to detect and quantify emissions at larger spatial scales between approximately 1 m to several hundred meters (site spatial scale) rely on techniques that are less well developed [18] in terms of their TRL i.e. less than TRL9 “actual system proven in

operational environment" [23]. Therefore, standardisation may require more pre-normative research and development.

A list of abbreviations and terminology used throughout this report are in Annex 3 and 4, Tables 7 and 8 respectively.

2. Development of standards

This section addresses the objective: *To identify gaps, current challenges and set requirements to facilitate the development of standards.* A LDAR scheme requires a monitoring method. An MCERTS scheme could form part of a monitoring methods lifecycle – as will be explained later in this section. The requirements of a monitoring method are dependent on an understanding of the emission source and data reporting requirement This section is structured as follows:

- How emissions should be described and reported.
- Lessons learnt from recent hydrogen measurement campaigns – the results of which are relevant for designing LDAR schemes.
- How to define data reporting requirements.
- To define what a measurement-based method is and its lifecycle.
- LDAR and MCERTS - how schemes could look like for hydrogen emission monitoring.

2.1 Emission sources

This section addresses the question: what do we need to know about production sites in order to specify LDAR monitoring method(s) and MCERTS standards?

2.1.1 Methods of hydrogen production

Gas reforming, electrolysis and gasification are the most common techniques of hydrogen production in England [24]. A brief summary of each and their Technology Readiness Level are given as follows:

Gas reforming

A process that uses heat and a catalyst to rearrange the molecular structure of hydrocarbons. A common technique is Steam Methane Reforming (SMR) using NG to produce a synthetic gas (syngas) consisting mainly of hydrogen and carbon monoxide. The syngas is processed further using the water-gas shift reaction to convert carbon monoxide into carbon dioxide [25]. Carbon Capture Utilisation and Storage (CCUS) can be

utilised to capture and store carbon dioxide to reduce its emission to the atmosphere. This technique is often referred to a *blue hydrogen* with CCUS and *grey hydrogen* without CCUS. SMR is at a high Technology Readiness Level (TRL9 – "actual system proven in operational environment") whereas an alternative technique *biogas reforming* (where biomass is used to provide biogas) is currently at a lower TRL (6 – "technology demonstrated in a relevant environment") [26]. Bio-methane (Renewable Natural Gas) uses the same core process as SMR, therefore it's TRL is 9.

Electrolysis

Electrolysis of water using a range of technologies such as: Alkaline Electrolysers (AE), Proton Exchange Membrane (PEM), Anion Exchange Membrane (AEM) and Solid Oxide Electrolysers (SOEC), using energy sources such as wind, solar and nuclear. This technique is often referred to as *green hydrogen* (or *pink hydrogen* if using nuclear as a source of electrical energy). These technologies are at various levels of TRL (5, "technology validated in a relevant environment" to 9 "actual system proven in operational environment") [26].

Gasification

Gasification using biomass (including waste) where organic materials are converted into a synthesis gas (syngas) containing hydrogen. These are at a low TRL (4, "technology validated in a laboratory") [26]. The main difference between gas reforming and gasification is the type of feedstock used, the former used gaseous hydrocarbons (e.g. Natural Gas), whereas the latter uses solid or liquid materials (e.g. biomass).

The above techniques are all included in the eligible pathways for hydrogen production to meet the UK Low Carbon Hydrogen Standard [27].

2.1.2 Scale of current and future production in England

There are several hydrogen production plants currently in operation [24] in England, which are electrolytic, use biomass or waste as fuel and one that uses methane reforming (without CCUS). These plants range in capacity from approximately 1Mega Watt (MW) to 50MW.

There are currently approximately 100 projects in England aiming to provide hydrogen production capabilities within the next 10 years, that are currently in the concept stage to undergoing construction. Based on current data [24]:

- Approximately 75% of these projects are based on electrolysis (using energy sources such as wind, solar and nuclear). Intended capacities range from 1 MW to 1000 MW per project, average capacity ~ 100 MW per project, totalling ~ 6000 MW for all projects.
- The remainder are categorised as CCUS-enabled using a range of technologies to convert a range of different hydrocarbon fuel sources to create a syngas from which hydrogen is extracted. Capacities from 1 MW to 2650 MW per project, average capacity ~ 900 MW per project, totalling ~ 13000 MW for all projects.

Some of these projects are included in the UK Government's Hydrogen Allocation Round (HAR) for Electrolytic projects: 11 successful awarded projects (HAR)1 [28] and 27 shortlisted projects HAR2 [29]. The permitting of many small sites could present a challenge in terms of the costs associated with measurement depending on the frequency of LDAR campaigns that need to be carried out. Examples of plants or projects linked to hydrogen production include biomass gasification, water electrolysis, and autothermal reforming of Natural Gas (NG) or Renewable Natural Gas (RNG):

Gasification from biomass

Figure 4 is a general block diagram of the process to generate biohydrogen from biomass. The feedstock typically consists of household waste, waste wood and agricultural waste. The preprocess stage involves shredding, sorting and drying the feedstock. The production of syngas involves heating the pre-processed feedstock in the presence of limited oxygen, the output of which is syngas and residues such as ash and tar which must be removed to produce the clean syngas. The post processing involves cleaning, purification and compression prior to storage and transportation.

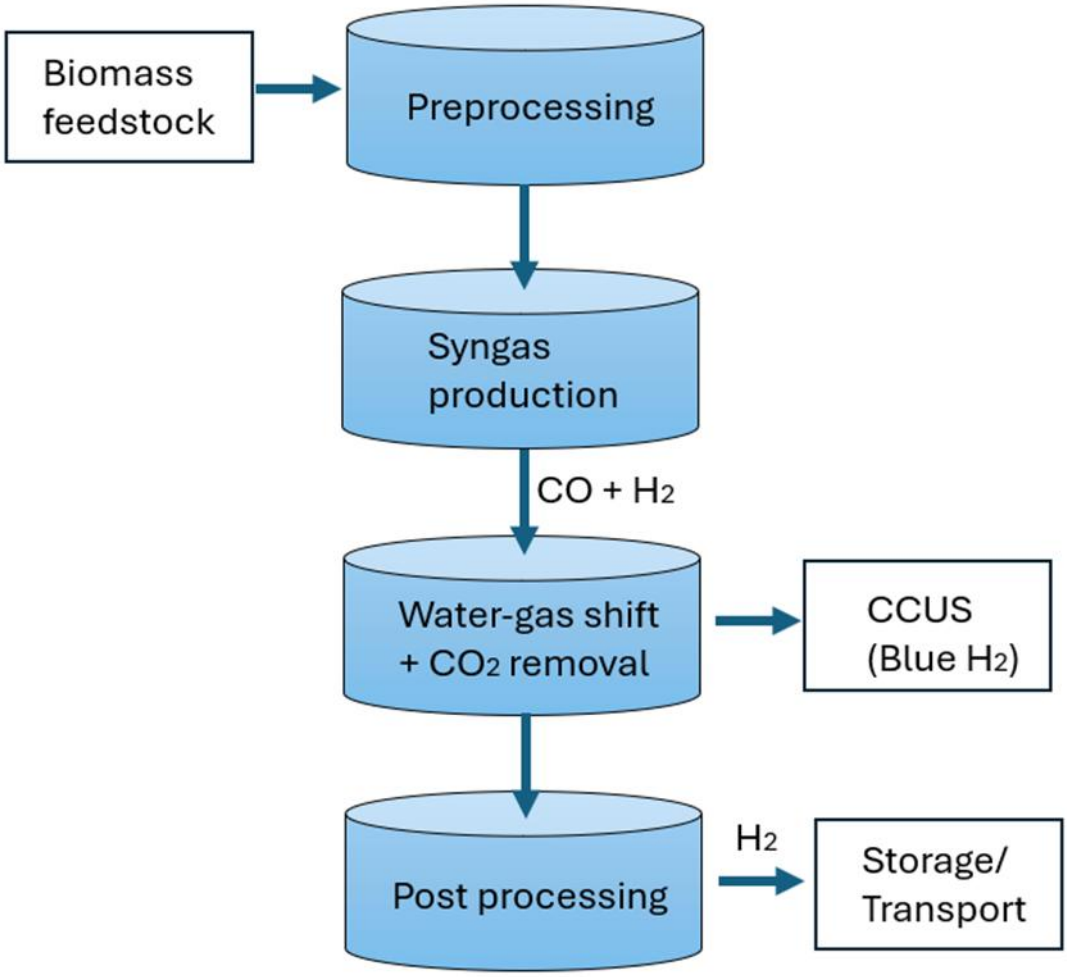

Figure 4. General process block diagram, gasification from biomass.

Electrolysis from solar

Figure 5 is a general block diagram of the process to generate hydrogen from an electricity supply using electrolysis. Examples of such as site are Barrow Green and Bradford Low Carbon both in the north of England, which are currently under construction, estimated completion 2026 and 2027 respectively.

Initial production capacity: 21 and 35 MW respectively. Peak production capacity: 35 MW

Large capacity electrolysis-based projects such as Sizewell (1000 MW) and Easington (1000 MW) are still in their feasibility stage, to be 2030 and 2028 respectively.

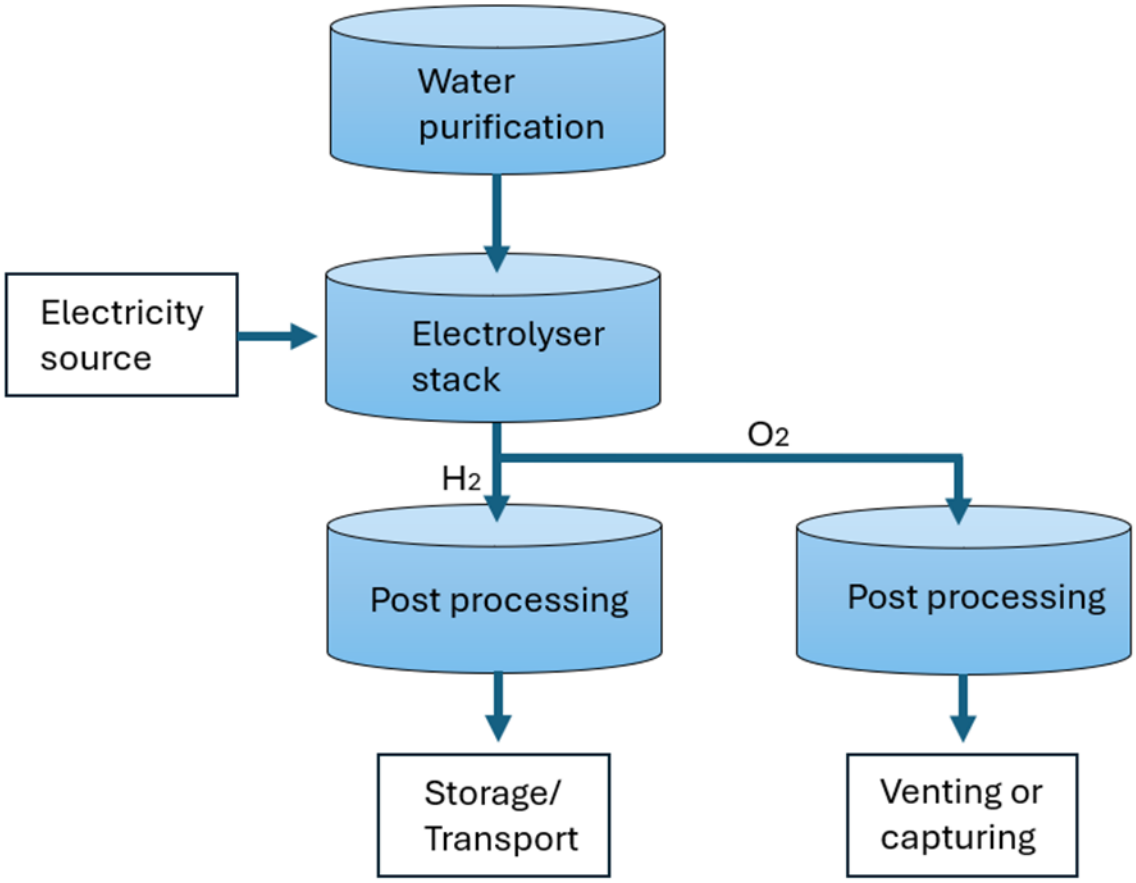

Figure 5. General process block diagram, electrolysis from electricity source such as wind, solar and nuclear.

Auto Thermal Reforming (ATR), from NG or RNG

ATR is similar to SMR. The former consists of the simultaneous combination of partial oxidation with steam reforming, exothermic reaction, high temperature (typically 700 to 1100 ºC) as opposed to the latter which is a reaction with hydrocarbons with steam (as previously described), endothermic reaction at a lower temperature (typically 500 to 700 ºC). Both processes produce syngas (hydrogen and carbon monoxide). The former is considered to be more efficient, but a more complex process.

An example of such a site is HyNET hydrogen production plant HPP1, northwest England, which is under construction, estimated completion 2026. The plant is CCUS enabled. Initial and peak production capacity: 350 and 1350 MW respectively.

2.1.3 Predicted sources of emissions from production

The main predicted sources of emissions through the hydrogen value chain are [12] [27]:

- Venting that occurs during startup and shutdown or deviations from normal operation such as activation of safety valves. Emissions from venting are predicted to be between 0.05 to 0.6% of hydrogen produced.
- Purging (relevant to electrolysis and SMR). Up to 10% of hydrogen produced may be released.
- Venting of residual hydrogen in by products, examples: carbon dioxide from steam reforming) up to 0.03% of hydrogen produced may be released; electrolysis, hydrogen in vented oxygen (hydrogen cross over) 0.05 to 0.15% of hydrogen produced may be released.
- Fugitive emissions due to permeation through compressor seals, on-site storage such as cylinders (depending on storage pressure, cylinder material, valve type) and boil off from liquid hydrogen storage.
- Fugitive emissions from leaks in pipes, flanges, seals, joins, valve seats or other components, due to component or operational failures (e.g. poor maintenance). Some literature sources suggest that leaks from components are predicted to be negligible [12], based on the assumption that infrastructure is purpose built for hydrogen and therefore due to its inherent design there shouldn't be leaks. However, currently there is no evidence to support this assumption. Other literature sources suggest, emissions (leaks) up to approximately 9% of hydrogen throughput [30]. This discrepancy may be due to interpretation of terminology, for example whether emissions from a pressure release valve is classified as a fugitive emission (leak) or a vented emission.
- Unburnt hydrogen from flaring is predicted to be negligible due to high flammability of hydrogen.

The focus of this work is fugitive emissions from leaks from components such as pipes, flanges etc and fugitive emissions from permeation – at component level (i.e. measurement close to the source of the leak). Other types of emissions from vents and sources of combustion are not the focus of this work.

The guidance on hydrogen production, emerging techniques [31] includes details on how to prevent or minimise emissions (to air) for hydrogen production facilities with carbon capture – covering techniques for venting and post combustion.

2.1.4 How emissions sources are described

To specify a monitoring method, the following information about the emissions source should be obtained [20], this information will be referred to later in the report to assess the scope of monitoring methods being developed:

- Temporal profile of the emission (continuous or discontinuous). Can a snapshot measurement be used to calculate a representative of the total emission of a year?
- Likely range of concentrations and emissions rates, based on the type of source and local environment.
- Gas composition.
- Likely interfering species, e.g. methane (SMR processes).
- The types of emission source: point, diffused, ducted or elevated. This may determine the range of concentrations that may need to be measured and sampling strategy (how and where the measurements are taken). For example, for point source vented emissions or ducted emissions up to pure hydrogen may need to be monitored; this would affect the choice of sensor technology. Elevated sources may be difficult to access.
- Environmental factors, for example humidity, temperature and wind may affect concentration measurements.

It is necessary to understand the type of components and component arrangements (for example: orientation, physical accessibility, height) as this could inform sampling strategy (i.e. how and where to take measurements), for example, due to hydrogen's buoyancy and to help locate the source leaks lower (height) components should be surveyed first. Also, it would be useful to understand which particular components, types of components or their arrangements could contribute most to emissions. The following (not exhaustive) are the range of types of components that are likely to be found at a production facility and are potential sources for leaks:

- Compression fitting.
- Flange.
- Plug.
- Valve, valve stem and valve seat.
- Pressure release valve.
- Regulator.
- Regulator thread.
- Reverse thread valve.
- Threaded fitting.
- Pump or compressor seal.
- Process drains.
- Open-ended lines.
- Seals (e.g. access door).

2.1.5 Measurements undertaken at test sites

A study was carried out by NPL on 3 sites for the Department of Energy Security and Net Zero (DESNZ), using a sniffer-based technique to screen (to detect the presence of hydrogen) and a high flow-based technique to quantify hydrogen emissions. An overview of these techniques is described in Section 3. These sites were:

- A research site that uses repurposed infrastructure originally design for NG. This was the largest site contributing the majority of components included across the three sites (829 of the 1129 components in the study).
- An industrial site where NG infrastructure was replaced with new hydrogen infrastructure.
- A site designed specifically for hydrogen.

This investigation covered a total of 1129 components, across the three sites, and discovered 48 “potential emissions”, whereby a concentration of hydrogen gas was measured at the leak interface. Normally, a threshold concentration is used to classify the presence of a leak, such a threshold was not used in this case. Of the 48 potential emissions identified, 34 were quantified with leak rates measured between 0.005 and 8.488 L/min, with most toward the lower end. Some of the smallest leaks were not

quantifiable as no hydrogen concentration was recorded in the high flow sampling flow, since in this case the sampled gas has become so diluted (by the high flow) to be below the limit of detection, in this case 10 parts per million (ppm).

Although it is difficult to tell how representative these sites are, of the potential emissions that could be quantified the most common component monitored were plugs, where unused ports were sealed off with solid threaded parts and tape was often used to ensure a seal, followed by flanges and compression fittings.

Where potential emissions could not be quantified this was sometimes because the component was only pressurised occasionally, e.g. located after a pressure relief valve, and the emission did not last long enough to quantify or could not be located again. Therefore, it is important to have information regarding the status and activities on the site to gain confidence on whether that data collected covers the site (both temporally and spatially). However, some irregular activities may not be monitored.

Some comparison of high flow attachments was made, bag attachments generally provided higher emissions estimates than nozzles. The main challenge is in fully capturing the emission and the greatest improvement in accuracy and repeatability comes from improved sample capture. Based on experiments using the high flow with a controlled leak rate it was found that the *maximum leak rate observed was likely to be representative of the true leak rate,* below the maximum is likely to be an underestimation. Overestimation of the leak rate was only likely under certain circumstances, such as when individual sources of leaks are closely separated or local, stable conditions cause gas to pool in an area.

An uncertainty based on the calibration of the flow and concentration measurements was used for individual quantification measurements of an emission leak rate and was typically below 25% (29 out of the 35 quantified) but could reach as high as 128% for the emission below the detection limit, which was deemed invalid, and 55% otherwise. Were an average of a set of repeat measurements taken as the quantification of emission rate an uncertainty based on the variability between these repeat measurements could be calculated. However, as mentioned, the highest individual quantification has been shown to correspond more closely to the true emission rate compared to the average.

Challenges of leak detection and quantification:

- Components that are out of physical reach for detection by sniffing and passive sensor techniques and high flow-based techniques.
- For the high flow sampler, instruments capable of measuring below 50ppm in outdoor conditions are needed so that they can measure the diluted gas concentration within the sampled high flow.
- Quantifying leaks where there is a high density of components or complex component parts – difficult to achieve full capture of the sampled gas.
- Acoustic cameras could be considered instead of sniffer-based detection in “out of reach” circumstances. Some cameras do not have quantification capabilities; it is unclear how reliable the quantification is from the models that do have a quantification capability.

Acoustic cameras detect the acoustic energy (ultrasound) emitted by a leak (a summary of acoustic camera function is provided in Section 3); therefore, the camera must be capable of detecting this acoustic energy amongst noise and sources of interference. The acoustic energy emitted depends on the characteristics of the leak (e.g. orifice size, pressure difference). Factors such as physical coverings (e.g. lagging) can block or attenuate the acoustic energy and reflections from nearby surfaces can have an impact on the measurements too. It is not necessarily the magnitude of the leak which determines whether it will be detected. An acoustic imager was used at one site in the DESNZ study but was only able to find one of the smaller leaks, but failed to detect a larger leak, for reasons outlined above.

2.2 Data reporting requirements

The primary driver to minimise emissions is regulation, but there is an economic and safety incentive to do so too. There are plans to regulate production facilities in England whereby site operators may require permits to operate. Permitting aims to protect the environment by compliance with regulations and encourage best practice in the operation of sites. Compliance will require evidence based on quantitative measurements and repairs will require accurate localisation of leaks.

UK hydrogen emissions regulations are primarily driven by the UK Low Carbon Hydrogen Standard - GOV.UK [27]. The standard establishes criteria for hydrogen production to be classified as low carbon. Compliance with the standard has two key parts: “consignment” (a discrete batch of hydrogen) compliance and “hydrogen production facility” compliance. For a consignment to be compliant it should have a final Green House Gas (GHG) emissions intensity of less than 20 g of (Carbon Dioxide) CO_2 per Mega Joule (MJ) of hydrogen product and be produced at a compliant facility, the criteria for compliance are described in [27].

The GHG emissions intensity is calculated from activity data, for example: input supply (e.g. feedstock), processes (e.g. CO_2 capture), output (e.g. waste) and calculations of fugitive non-CO_2 losses (e.g. methane slip, Nitrous Oxide and Hydrofluorocarbons). Fugitive hydrogen emissions are not currently required to be included in the calculations, however, these emissions should be minimised and reported separately as described in the standard (Chapter 10), using a risk reduction plan and reporting template [32]. It should be noted that the term fugitive in the standard includes vented emissions and emissions from sources of combustion as well as leaks. The standard states that hydrogen production facilities shall provide the predicted fugitive hydrogen emissions in kg pure hydrogen per year. This estimate shall include a breakdown of different emissions source types: i.e. process vents, compressors, on-site storage, flares (expected to be negligible), leakage through pipework and joins (expected to be negligible).

Such predictions should be validated using measurements of emissions. It may not be always practical or accurate to estimate emissions using calculations since fugitive emissions are complex (i.e. their type, composition, spatially and temporal etc), therefore measurement-based methods (to estimate emissions to atmosphere) are needed. Measurement-based methods may also be needed to cover vented emissions, sources of combustion and diffused emissions from permeation. This report focusses on leaks.

The primary purpose of a LDAR programme is to detect, locate leaks, by measuring gas concentration. However, it is difficult to rely on concentration to represent an emission, particularly hydrogen, as its characteristics are different to gases such as methane and there is less experience in understanding the behaviour of hydrogen emissions. For example, the plume from the leak will be transported (buoyancy and diffusion) away from

the source and become diluted. The measured concentration will also be affected by factors such environmental conditions (e.g. wind), the physical characteristics of the source (e.g. a single hole or diffused leak around a flange) and the gas composition (i.e. preferential emissions of different gases). Therefore, undertaking a LDAR scheme should include quantification to provide evidence data to help improve the understanding of emissions from different components, data for reporting (environmental compliance) as well as detecting and localising leaks for repair. EN 15446 include the use of correlation factors to quantify leaks from concentration measurements using an existing (vast) library of data. Such a library does not exist for hydrogen.

The suggested data requirements for a LDAR programme are:

- Detection and Localisation of emissions at component level (<1 m spatial) that are above a defined concentration threshold.
- Mean emissions rate and uncertainty, where the mean and uncertainty are calculated from a set of measurements with a coverage factor.
- Time and location of the measurement.
- A record of the measurement conditions: temperature, humidity and wind (if applicable).
- Site process activities, conditions and status at the time of measurement.
- The period of LDAR monitoring cycles (e.g. yearly) and coverage of a site.

Other requirements are:

- Remote sensing (to cover inaccessible areas).
- Species: Ideally hydrogen specific technique or a response factor calculated for a non-specific technique (to take into consideration blended gases if applicable).
- To consider sources of interference such as methane.

2.3 LDAR requirements

This section describes what a monitoring method should consist of, as a LDAR scheme will be based on a method, followed by describing LDAR in other sectors and the describing what a LDAR scheme for hydrogen could consist of. It is anticipated that a scheme will be based on methods being developed under the NHyRA project [21], a review of their scope and implementation is given.

2.3.1 What a method should contain and its lifecycle

This report covers measurement-based methods, not methods that estimate emissions using engineering calculations or the application of emission factors.

A monitoring method must be underpinned by robust metrological principles to ensure that the data they provide can be trusted. A method should contain the following [18]:

- Scope, including: a clear definition of the physical magnitude to be measured (i.e. emission rate) and its uncertainty, limitations, assumptions and dependencies.
- Measurement objectives: in general, how the measurements have to be performed and a set of procedures that include planning preparation and implementation.
- Sampling strategy: defines specifically the frequency and location of measurements, and how the measurements are collected and assimilated into a report.
- Training and competencies that include: evidence of validation and conditions under which the tests were performed, calibration and traceability, applicable standards and a quality system to provide confidence in data.
- Recommended instruments and techniques and the performance and evaluation requirements for instruments.

Figure 6 shows the lifecycle of a monitoring method. The aim of a monitoring method (that is part of a LDAR scheme) is to provide a data product that meets the data reporting requirements outlined above. Part of the role of an MCERTS scheme is to verify use of a method at a given time by carrying our surveillance activities and performance tests. The validation involves laboratory tests, tests against a controlled release of hydrogen and tests at representative sites across the hydrogen value chain.

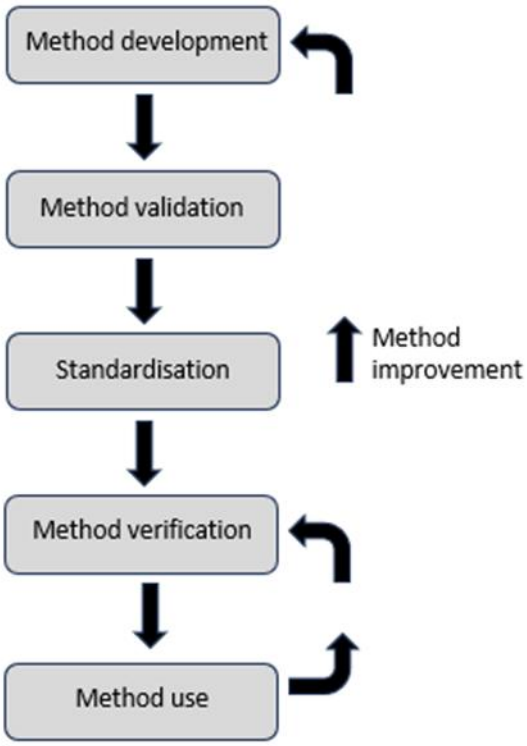

Figure 6. Lifecycle of a method [18].

2.3.2 LDAR in other sectors (e.g. NG, NMVOCs)

A number of the European Union's Best Available Techniques (BAT) reference documents include LDAR schemes: examples are waste treatment [33] (BAT conclusion 02018D1147) , waste gas management and treatment in the chemical sector [34] (BAT conclusion 32022D2427), refining of mineral oil and gas [35] (BAT conclusion 02014D0738) which include LDAR based on the sniffing technique described by EN 15446 [22]. In addition, the BAT includes: Optical Gas Imaging (OGI) [36] for monitoring at component level and Differential Absorption Lidar (DIAL) [37] and Reverse Dispersion Modelling (RDM) that are more suited for wide area and site level monitoring [38].

EN 15446 is specifically a method for estimating fugitive and diffuse emissions of Volatile Organic Compounds (VOCs) from components, it is a modified version of the US Environmental Protection Agency's (EPA) method 21. EN 15446 is based on the snap-shot measurement of gas concentration at the interface of a leak using a portable instrument. The measurement is then converted to a mass emission rate using a set of

correlations. Correlation factors have been obtained by analysing data gathered over many decades from thousands of leaks in the gas and petrochemical industries. The most frequently used sets of correlations are those published by the EPA, or for high concentrations (above 100,000 ppm), an emission factor is used [39]. However, all these factors are restricted to VOCs. For hydrogen, no such correlations or emission factors exist; such data would need to be generated, compiled and validated if this approach were to be adopted.

EN 17628 [40] is a standard set of methods for measurement of fugitive and diffuse emissions of VOCs into the atmosphere, this standard includes OGI, DIAL, SOF, RDM and Tracer Correlation (TC). It specifies a system of techniques to detect, identify and/or quantify emissions and is complementary to EN 15446. Although the method has been validated for NMVOCs it can be applied in principle to methane and other gases.

DIAL and SOF are based on absorption spectroscopy, there would be insufficient sensitivity for these techniques to be applied to the monitoring of hydrogen (over wide areas); RDM and TC could be considered, but require technical development [18].

2.3.3 LDAR for hydrogen

OGI, which is used to survey for leaks at component and functional element level, is based on absorption spectroscopy. Techniques are being developed to detect tracer gases within the hydrogen gas stream (such as CO_2) [18], but an addition of a tracer gas may not be desirable where gas purity needs to be maintained. An alternative technique are acoustic cameras that measure acoustic emissions generated by a leak (i.e. the escape of gas passing through a hole). A recent study recommends techniques for monitoring at component level [18], such techniques are:

- Leak detection at component level using passive sensors and sniffer techniques.
- Leak detection and quantification at component level using the high flow technique.

Methods are currently being developed and validated under the NHyRA project [21] , expected completion early 2027:

- Detection at component level using portable gas detectors and acoustic cameras: Hydrogen leaks generated from equipment and pipes (component scale).Specific techniques employed are: passive sensing and acoustic cameras [21].
- Fugitive emissions quantification using the high flow technique: Hydrogen leaks generated from equipment and pipes (component scale). The specific technique employed to quantify emissions is high flow sampling [41].

2.3.4 Method scope and implementation

The methods being developed and validated within the NHyRA [21] project are designed to monitor fugitive hydrogen (in its molecular form H_2) emissions generated from equipment and piping leaks using manual measurement-based techniques. They could be applied throughout the value chain (hydrogen production, transmission distribution and end users). The methods consider only above ground fugitive emissions; underground or underwater leaks are not included in their scope. The range of components within scope are listed under the previous subsection: *Predicted sources of emissions from production*. However, the feasibility of applying these methods will depend on the nature of the specific components that need to be monitored (e.g. accessibility). The scope of the methods (leak detection and leak quantification) being developed and validated under NHyRA are described as follows:

Leak detection method: This method can be applied in periodic inspections carried out at component scale and can be used in LDAR schemes or any other situation for the detection of hydrogen gas leaks. The method is based on two complementary techniques:

- The measurement of gas concentration resulting from escaping gas that has blended with the atmospheric air near the leak source. The concentrations are measured using a portable instrument that either use a passive detector or a sampling pump (‘sniffers’) to draw in the sampled air to a detector. This technique requires physical access to the source of the leak. The method is based on EN 15446:2008.
- The measurement of acoustic emissions to air caused by escaping gas. The acoustic intensity is measured using a portable acoustic camera that provides a graphic image of the acoustic intensity to the user. Such cameras provide can provide an indication of a leak but should be combined with other techniques such

as sniffers or foaming solutions is verify the presence of a leak. Figure 7 shows two examples of images from an acoustic camera. The acoustic intensity is shown on a colour scale and overlayed onto a visual image.

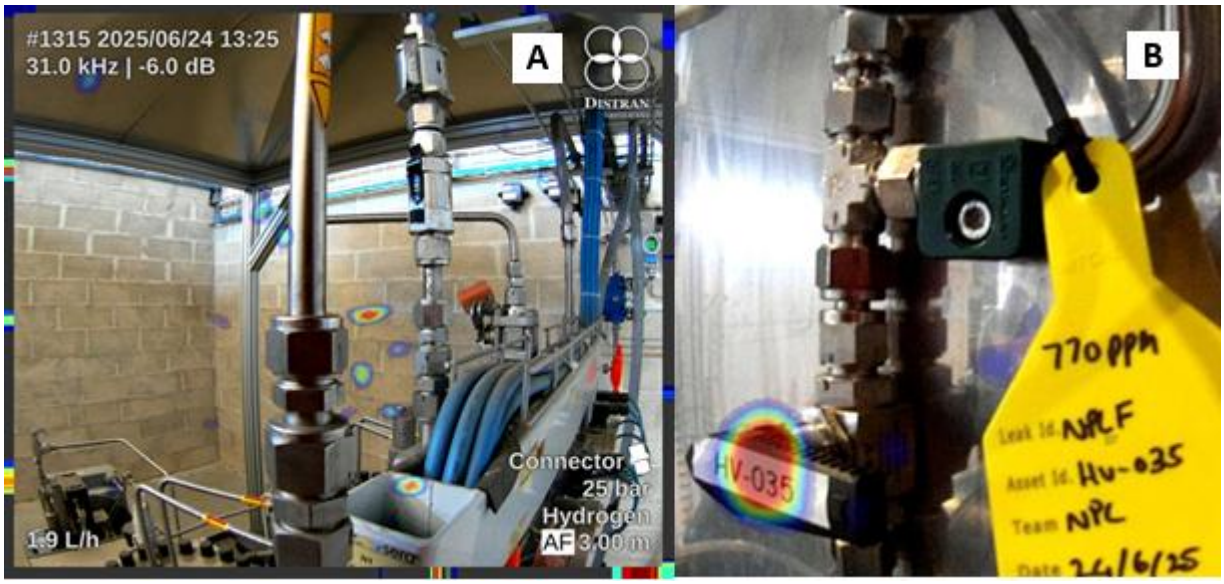

Figure 7. Images from an acoustic camera: (A) site view showing acoustic intensity (shown as colour spots) annotated onto a camera visual view and (B) zoom of a larger intensity at the position of a valve. INIG, Poland copyright permission to be shared, 2026.

The leak detection method does not recommend any specific instruments but includes instrument criteria and performance requirements. The minimum detection limit of this method has yet to be defined.

Leak quantification method:

This method uses the high flow technique which is based on a portable “vacuum cleaner” type instrument capable of drawing in ambient air and capturing the escaped gas with it. A handheld hydrogen gas detector is integrated into the instrument to measure concentration that is then combined with a measure of flow to obtain leak rate. The method is in two steps: leak detection and localisation (using the previously described leak detection method) followed by quantification. The high flow technique involves physically coupling to the component to ensure that the whole leak is captured. The method has been developed and currently being evaluated using a specific instrument for concentration measurement. The method for uncertainty calculated in the reported data and its minimum quantification limit has yet to be defined.

The methods outline the safety procedures, preparation before measurements, maintenance and procedural use, specification for instrumentation and performance criteria (including response time, calibration precision) and calibration gas requirements and specific considerations for the use of acoustic cameras (leak detection) and reporting requirements.

Neither method prescribes the number of potential emission sources to be screened nor the frequency at which these sources should be screened. The sampling strategy (specific details on when, where and how to take measurements) will need to consider the site's characteristics and the required level of control over fugitive emissions.

Considerations on the use of these methods based on the characteristics of the emission source:

- Temporal profile of emissions: These methods are not designed to provide continuous measurement; therefore, the operational status of the site and the components being monitored needs to be understood to ensure that the snapshot measurements taken can be used to provide a representative yearly total emission.
- Range of concentrations. The methods do not propose a threshold for concentration that would indicate the presence of a leak as this depends on the scope of the survey and on the specific features of the site being monitored. The threshold must be above the Limit of Detection which will be dependent on the instrument's design and sensor technology used. The methods are to be used where the leaking hydrogen gas has mixed with the atmosphere up to 10% of LEL (or 0.4 %mol/mol). The methods (including the instrument performance criteria) as they stand may not be suitable for direct monitoring of vents or ducted emissions depending on the concentration of the sampled gas.
- Gas composition. The detection method can be used for monitoring components that contain pure hydrogen or a blended gas mixture containing hydrogen. Limitations on concentration (detection threshold at the lower end and linearity at the upper end) will fundamentally depend on the sensor technology, for example Metal Oxide Semiconductors (MOS) and Catalytic sensors require Oxygen, whereas Thermal conductivity and Palladium-Alloy sensors are capable of operating up to pure hydrogen concentrations. The selectivity of the sensor technology (or use of dual or multiple types of sensors) will determine on whether

hydrogen can be distinguished from other gases, for example MOS cannot, but Electrochemical sensors can be engineered to detect hydrogen only. The types of components that can be monitored will depend on physical accessibility. The quantification method assumes pure hydrogen (that has been diluted with the high flow air) as further work is required to investigate response factors for species like methane.

- Likely interfering species could influence the choice of instrument (leak detection method) and the sampling strategy. For example, taking background methane measurements in case instruments are employed that are not hydrogen specific (the specificity will depend on the instrument sensor technology [18]) and to ensure the correct application of response factors.
- The methods are suited for point source emissions (leaks) that have become diffused at component scale. They are not intended for monitoring highly diffused emissions over large area or site level, neither direct monitoring of vents or potentially ducted emissions (depending on the concentration range) and emissions from sources of combustion. However, the methodology could be adapted and instruments designed to suit these use cases. The ability to monitor elevated sources will depend on safe accessibility.
- The methods consider temperature, humidity and wind (which could dilute concentration), however they may not be suited to where there are large variations in temperature or humidity (e.g. close to a source of combustion) or where there are large variations in wind (e.g. closely spaced builds that generate a wind tunnel or an elevated position).

Assuming these (NHyRA) methods are adopted, technological and methodological gaps will be:

- The monitoring of vented emissions, ducted emissions and sources of combustion.
- Monitoring of discontinuous (unpredictable) fugitive emissions that require continuous measurement.
- Physically inaccessible areas.
- Fugitive emissions diffused over a wide area, e.g. storage areas and pipelines and permeation through seals.

Some instruments or methods (e.g. engineering controls) may require some adaption to work in specific environments, e.g. areas of large temperature variation, humidity (e.g. combustion) or wind disrupting the measurement of a component in an exposed location.

However, as stated these could be addressed by adapting existing methodology and designing instruments to suit the emission characteristics and data reporting requirements. Measuring emissions from venting and purging could be addressed by [18]:

- Using an installed instrument to continuously measure flow rate providing the emitted gas composition is known, using sensors such an anemometer.
- Temporarily installing or locating an instrument close to the vent, such as calibrated vent bag (to capture a sample that would be subsequently analysed) or an appropriately designed sniffer instrument.

Lessons learnt from measurement campaigns (funded by DEZNZ) are:

- A pumped sampler is preferred to a passive sensor, but physical reach can be limited. An acoustic camera should be considered for components that are out of reach.
- High density of components can make quantification challenging and provides challenges for acoustic cameras. For very closely space components, a foaming solution was used to find the leak location.
- Where components were arranged vertically and conditions were stagnant it was found best to start from the bottom and work up due to the buoyancy of hydrogen.
- Awareness of restricted zones, e.g. European Union safety directives for explosive atmospheres [42] (ATEX) is needed to ensure the appropriate certified instruments are used.

Figure 8 is a flow chart (created by NPL) that represents an example of how a user could be guided on the choice of technique based on physical accessibility and whether the measurement needs to be performed in a restricted (i.e. explosive) zone. This example is for leak detection at component level and could be expanded for emissions monitoring in general and form part of a general guidance. For example, if the leaking component is accessible then the preference would be to use a sniffer. Such a diagram could highlight capability gaps, for example if a component is not physically accessible then (currently) there is not a reliable method for leak quantification.

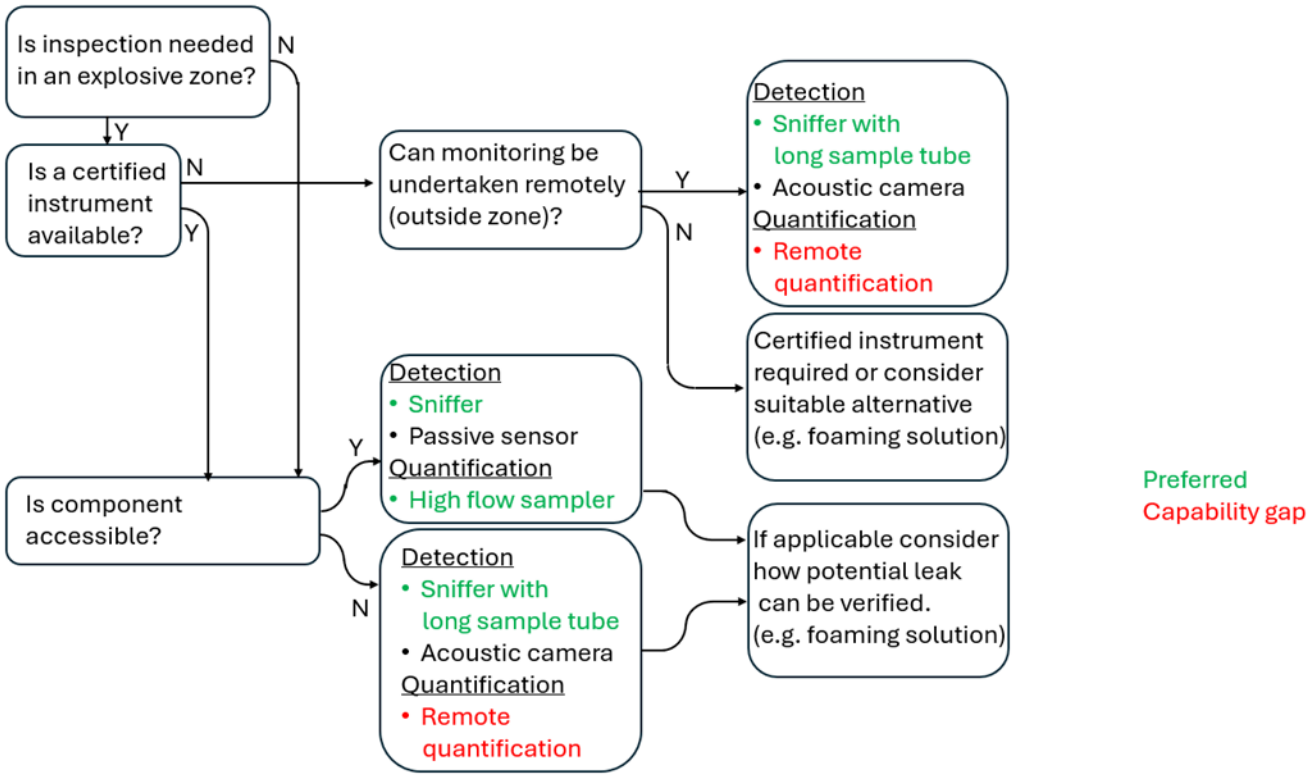

Figure 8. Choice of technique based on leak location and accessibility

2.4 MCERTS requirements

A monitoring method (that would be implemented as part of a LDAR programme) should routinely undergo periodic verification to check that it complies with defined criteria and quality control procedures on a given day. An example of a verification process is a Proficiency Test (PT) scheme [43]. A PT scheme is an inter-laboratory comparison of results from test samples to assess the performance and competence of laboratories in their use of methods. Another example is the Environment Agency of England Monitoring Certification Scheme (MCERTS) scheme, such a scheme may describe the certification of personnel and equipment and the accreditation of organisation(s) to demonstrate compliance with quality requirements and post compliance surveillance to ensure the requirements are being met.

2.4.1 The structure of an MCERTS programme

There are three key components to MCERTSs:

- **Product certification**: Instruments used for monitoring must meet MCERTS performance standards.
- **Personnel certification**: For some MCERTS schemes (e.g. stack testing) individuals performing tasks must be certified under MCERTS competency standards; within this are personnel qualifications, for example MCERTS level 1 and 2. However, not all MCERTS schemes are required to have a personal competency aspect; in which case competency could be achieved by in-house training which is independently verified and audited by an external party such as UKAS. The appropriate level of competency and proof of competency for the monitoring of hydrogen will need to be addressed, which may depend on the technique (e.g. sniffer, high flow, acoustic camera etc).
- **Organisation accreditation**: Laboratories and monitoring service providers must be accredited (usually to ISO/IEC 17025) and comply with MCERTS specific requirements.

As part of an organisation's accreditation a PT scheme could be implemented.

The scope of this report is the development of an MCERTS scheme for the methods being developed under NHyRA (i.e. leak detection at component level and leak detection and quantification at component level) which use handheld portable instruments. Currently, there is no MCERTS scheme covering the fugitive monitoring of emissions. MCERTS only covers the monitoring of ambient air and stacks. An approach could be to use the following as a basis to develop a scheme:

- MCERTS performance standards for Handheld Emissions Monitoring Systems (HEMS) [44], which refers to:
  - EN ISO 9001:2015 [45]. Requirements for quality management systems. EN 15267 [46]. Air Quality. Certification of Automated Measurement Systems (AMS). Methane is in scope, but not hydrogen.
  - EN 15267 part 1 and 2 are for air quality monitoring equipment, so in principle hydrogen could be in scope. Also, part 4 performance criteria and test

procedures for portable AMS that carry out periodic measurements. However, for fugitive hydrogen emissions a new standard will need to be produced. i.e. an MCERTS standard equivalent to EN 15267 part 4.

- MCERTS personnel competency standard: manual stack emissions monitoring – dependant on the level of competency required to undertake the monitoring method [47]. This defines levels of competence from trainee to team leader and how conformance to the different competency levels is assessed and maintained, and supervision requirements. As mentioned, the level of competency will depend on the monitoring technique.

2.4.2 The requirements of an MCERTS programme for hydrogen

An MCERTS scheme for hydrogen applied to the techniques such as those being developed under NHyRA [21] (i.e. detection and quantification at component level scale using handheld instruments) could be based on EN 15267 parts 1,2 and 4. EN 15267 is applicable to periodic measurements. Although EN 15267 part 4 is applicable to automated measurements, in principle instruments that meet the performance requirements could be certified under this standard.

EN 15267 structure (note that part 1 and part 2 apply to any type of air quality monitoring equipment, so these will apply directly to hydrogen):

- **Part 1:** General principles of certification including requirements for testing laboratories and certification bodies. Performance tests consist of laboratory and field testing. Laboratory testing is designed to assess whether the monitoring method and associated instrumentation can meet, under controlled conditions, defined performance criteria. Field testing at several different sites is designed to assess whether the monitoring method and associated instrumentation can continue to meet the defined performance criteria within a real-world scenario. There is an initial assessment of the manufacturers quality management system, followed by certification and then periodic surveillance (described in part 2). The roles and responsibilities of the manufacturer, test laboratories and the certification body are set out in the standard.

- **Part 2:** Assessment of the manufacturer's quality management system and post certification surveillance to ensure continued compliance.
- **Part 3 and 4:** Performance test criteria and test procedures for continuous monitoring and performance criteria for periodic measurements respectively. As stated, a new standard will need to be produced for hydrogen fugitive emissions.

There are general requirements for instruments such as complying with UK CA / CE marking (e.g. Electromagnetic Compatibility Directive), the ability to "zero" the instrument readout and provide an indication of the instrument's operational status (e.g. standby, normal, maintenance modes) and offer a degree of protection against dust and water and requirements for storage and transport.

2.4.3 Proposed performance characteristics

A list of performance characteristics is in EN 15267 part 4. The relevance of each performance characteristics and its performance criteria will depend on the monitoring method technique (instrument), e.g. for a high flow instrument the effect of flow rate will have to be considered. The testing of acoustic cameras needs to be considered, i.e. whether acoustic cameras can be included, what performance metrics would need to be assessed and additional metrics that would need to be added to the standard; the same would apply to a tracer based OGI technique. The data reporting quality requirements will also need to be considered too, e.g. minimum detection limit and range and uncertainty, this will then determine the specification and requirements of the test equipment.

The draft methods being developed and validated under NHyRA [21] include instrument specification (e.g. measurement range, requirements of the work permit) and performance criteria (i.e. response time and calibration precision). The draft method describes when to undertake these tests, for example the response time should be tested each time a new instrument is put into service for the first time or if there has been a modification that could influence response time. MCERTS certification would need to meet the specifications and performance criteria set out in the method. Tables 1 and 2 (left hand column) list the laboratory performance and field performance criteria defined in EN 15267 part 4. The right-hand column discusses the applicability to the NHyRA methods under development. It's not the aim of this report to specify criteria values, ranges or thresholds. These could be based on the NHyRA validation work and be published in the future.

Note: the draft methods refer to the maintenance and calibration protocols recommended by the manufacturers.

Table 1. Laboratory performance testing criteria from EN 15267 part 4.

Criteria	**Applicability to the methods under development**
Response time	These tests are included in the method validation programme (being undertaken within NHyRA). The methodology could be included and adapted for an MCERTS test.
Lack of fit (linearity)	
Influence factors: Environmental (e.g. temperature, humidity) and cross sensitivities	
Repeatability of standard deviation at zero point	Needs to be defined and included.
Repeatability of standard deviation at span point	
Short term zero and span drift	
Influence of voltage variations	This criterion is not included within the MCERTS handheld emissions monitoring standard, but there will need a warmup time test.
Influence of flow rate	Applicable to sniffer and high flow instruments.
Response factors	Must be considered for blended gases.

Table 2. Field performance testing criteria from EN 15267 part 4.

Criteria	**Applicability to the methods under development**
Response time	These tests are included in the draft methods. The methodology could be included and adapted for an MCERTS test.
Short term zero and span drift	Needs to be defined and included.
Reproducibility	

Under the EN 15267 standard, the uncertainty is determined from the field (reproducibility) or laboratory (repeatability), whichever is greater. In addition, the draft methods include calibration precision tests and tests for flow-rate uncertainty (high flow technique).

The results from these tests (method validation) would be used to revise the method being developed, for example, response time, a measurement can only be valid after the response time (i.e. time period between exposing the sensor to the gas plume to a readout from the instrument). The method would then either become a standard or be used to inform a best practice guide. Further, these results could then be used to determine performance test criteria as part of MCERTS periodic surveillance testing.

3. Current and emerging techniques

This section addresses the objective: *Collate existing knowledge of current and emerging techniques and their suitability, scope, limitations and availability.* This objective was addressed by building on previous studies:

- A report commissioned by the EA's CSG [12] that describes monitoring techniques
- A review of hydrogen monitoring methods [18].

This section summarises monitoring techniques and their associated instruments and sensor technologies by providing information on their scope performance and limitations. Applicability to handheld or automated techniques are described. A technique is a generic term used to describe a type of measurement instrument, sampling strategy, emissions quantification, or data process. For example: high flow, and acoustic cameras. A method contains many of these features and the elements described in Section 2 (e.g. quality control process).

The performance of a technique will depend on the sensing technology and the design of the instrument. The performance of the method will depend on the details of the elements employed, such as its sampling strategy and how measurements are processed into a report. For the purposes of this report, techniques are categorised as follows:

- Techniques that have been implemented in the draft methods being developed under the scope of the NHyRA project [21], i.e. leak detection and quantification at component level using handheld instruments.
- Other techniques that could be considered for leak detection and quantification at component level, commercially available and low TRL (below TRL 9)

A comprehensive list of techniques (and their scope) is given in a recent review (Methods for detecting and quantifying hydrogen emissions over a wide range of temporal and spatial scales, a state-of-the-art review, 2025) [18].

3.1 Leak detection and qualification at component level draft methods

The following describe the techniques that are used in the methods that are being developed under the NHyRA project. They all detect or quantify (as snapshot in time) fugitive emissions at component level, using handheld portable techniques. These techniques are passive sensing and sniffing, high flow sampling and acoustic camera. These techniques use instruments that are commercially available (apart from the high flow sampler), therefore the use of such techniques can be readily implemented once methods have been developed and validated.

3.1.1 Passive sensing and sniffing

These are systems which have a sensor on the end of a probe (passive) or pumped the ambient air that is sampled over a sensor (sniffer). A range of sensors can be deployed which use different principles to detect hydrogen, including catalytic combustion, electrochemical response or thermal conductivity changes [18]. Each sensor technology has inherent advantages, such as some can be low cost and capable of detecting hydrogen specifically (i.e. less susceptible to interfering gases), and disadvantages, such as being affected by interference (e.g. changes of humidity) or susceptible to certain usage or maintenance issues (e.g. susceptible to being poisoned by contaminants).

Where a pump is used the flow rate is typically between 0.2 and 1.2 litres per minute. When used for leak detection and location it is important for the sensor to have a fast response time (less than approximately 30 seconds) to the presence of hydrogen. These devices often measure the concentration of the gas allowing the detection and location of leaks but not quantification of the leak rate.

3.1.2 High flow sampling

This is based on the Bacharach HIFLOW® used to quantify the emission rate of methane leaks [48].The technique uses a high flow, up to 220 litres per minute, much higher than utilized by the pumped sniffers mentioned above, to capture gas released by a leak. The captured gas is then measured by an instrument capable of measuring hydrogen concentration. The system captures surrounding air when sampling and both the diluted

gas concentration and flow rate are measured allowing a quantification of the leak rate [18]. For accurate quantification it is important that the entire leak is captured and, to help achieve this, specialised attachments can be used.

Like with the passive and pumped sensor systems, high flow systems have been used by the natural gas industry and there has been some investigation into applying the technique to hydrogen use.

3.1.3 Acoustic cameras

Based on the principle that the escaping gas from a high-pressure leak will disturb the air, cause turbulence and producing audible and ultrasound waves which can be picked up by microphones. Acoustic cameras use an array of microphones to produce an overlay of a digital image where a colour scale is used to represent the intensity of sound. Unlike the passive and pumped sensors this allows detection of a leak from a distance, so that inaccessible components can be surveyed, but detection can still be difficult without line of sight. Most models of acoustic cameras do not allow the quantification and the accuracy of quantification for the models that do is unclear whether they can provide reliable results.

These techniques are complimentary, for example an acoustic camera could provide an indicative result, followed by high flow to quantify the leak. Table 3 is a comparison of these techniques.

Table 3. Qualitative and quantitative comparison of draft method techniques

Criteria	**Passive sensing and sniffing**	**High flow**	**Acoustic cameras**
Scope			
Method category	Detection and localisation at component level	Quantification at component level	Detection and localisation at component level
Sampling strategy class	Point sensor	Point sensor	Remote sensor

Emission source type	Fugitive leaks at component level		
Portability	Battery handheld instruments		
Advantages	Measures the concentration directly, so a more reliable measure of the leak compared to acoustic cameras	Quantification	Monitor inaccessible or hard to reach areas. Provide an indicative result over a wider area (compared to a sniffer)
Limitations	Physical accessibility, need to measure close to the source of leak. Detection only	Physical accessibility and coupling of the leaking area. Insensitive to small leaks. Untested for preferential leaks	Basic assumption is that the acoustic intensity observed is a function of leak size; however there are many factors that can affect the acoustic intensity observed, for example pipe material, physical objects that could disrupt the acoustic waves (e.g. lagging) etc. Although some models have a quantification function, based on the assumptions (described above), quantification could be unreliable.
Example instruments			
Example instruments	Teledyne GS 700 - Hydrogen*	Modified Bacharach HIFLOW® with Teledyne GS 700 -	Distran Ultra Pro X FLIR: Si2x-Pro

		Hydrogen instrument**	
Selectivity to hydrogen	Selective to methane (Infra-Red (IR) sensor) Nonselective to all other gases (Catalytic bead and Thermal conductivity sensors)		No

For instrumentation performance metrics (e.g. range of concentration, response time) please refer to the manufacturer's datasheet; the performance of which is dependent on the sensor technology, instrument design and the conditions of test. Performance metrics such as response time, linearity, sensitivity to environmental factors, drift, uncertainty and detection limit will be tested during the method validation under NHyRA.

* The Teledyne GS 700-Hydrogen instrument (gasmeasurement-gs700-h2-brochure-english.pdf) has the capability to specifically measure methane using an infra-red sensor. Catalytic and thermal conductivity sensors are used to detect hydrogen, but these technologies are non-selective, a comparison of different sensing technologies are given in reference [18]. Other instruments were cited in [12] using catalytic combustion, thermal conductivity and Palladium alloy sensors. The choice of instrument will depend on many factors such as sensor technology, physical design of the instrument (portability, certifications, e,g. ATEX etc), and how the instrument operates, for example can the output be zeroed for taking background measurements, how the measurements are processed to provide a readout (for example is humidity automatically sensed and factored in, averaging etc).

** The high flow sampler that NPL use is an adapted Bacharach hi-Flow sampler to measure hydrogen, it is not commercially available. As far as the author is aware the Bacharach hi-Flow sampler is no longer commercially available. There are alternative systems that can measure methane or NG, for example: SEMTECH HI-FLOW 2 or Hi-Flow Sampler for Fugitive Emissions Monitoring & Leak Detection.

3.2 Other techniques that could be considered for leak detection and quantification at component level.

This section provides a list of techniques that could be considered for detection at component level: foaming solutions, optical gas imaging (OGI) with tracer, colorimetric, sensor networks and distributed sampling, Micro-Electro-Mechanical Systems (MEMS), fibre optic based sensors and bagging.

3.2.1 Foaming solutions

This technique involves applying a soap-based solution to the component to be inspected. It requires a minimum gas pressure difference between the inside of the component and the outside. Detection is by observation of gas bubbles forming on the applied solution.

3.2.2 Optical Gas Imaging (OGI) with tracer

This technique could be used to infer the presence of a hydrogen leak or detect other (non-hydrogen) emissions. This technique captures a ‘snap-shot’ of emissions in time, it is a handheld portable technique and there are commercially available instruments, but the scope and performance of a method using this technique would need to be investigated.

OGI is a technique based on thermal imaging technology. OGI cameras designed for hydrocarbons require a 3.2-3.4um filter. By adding a spectral filter, a thermal imaging camera can be made to be specifically sensitive to infra-red active gases. As long as the gas exists in the field of view in sufficient concentration and there is a sufficient differential temperature between the gas and the background image, the gas plume can be seen in contrast to the background.

Hydrogen has limited absorption in the infra-red region. Therefore, the OGI technique cannot directly detect hydrogen leaks. However, there is interest in the possibility of using the OGI technique to detect leaks in the hydrogen value chain resulted in the development of a technique using a tracer gas in the hydrogen. Currently, carbon dioxide is a tracer added to hydrogen that enables the OGI technique to detect leaks in the hydrogen value chain [18], this reference cites research that has shown that adding carbon dioxide to hydrogen below 5% allows for effective optical imaging of gas leaks. However, the

additions of tracer streams may not be desirable for end uses where hydrogen purity is important (e.g., fuel cells). Such cameras require a spectral range of 4.2-4.3um to be sensitive to carbon dioxide.

An advantage of this technique is that it is a remote sensing method, so could be considered for monitoring inaccessible areas. This technique may have a niche roles, for example applied to blue or grey hydrogen sites, to detect upstream methane leaks, carbon dioxide or carbon monoxide leaks from processes.

3.2.3 Colorimetric

Colorimetric indicators are designed to cause colour changes in a material when they come into contact with hydrogen. They are promising candidates to meet the requirements of hydrogen detection in many technical applications; these indicators are low cost, don't require electrical power, and provide spatially resolved visualization in hydrogen leaks [49]. For example, DetecTape H_2 Visual Hydrogen Leak Detector is a silicone wrap that changes colour when exposed to hydrogen [50]. It can be applied to flanges or connections up to 40.25" in diameter, and it noticeably changes colour within 2 minutes of exposure. In this way, a leak can easily be localized upon inspection. This technology is commercially available. These types of sensors provide a qualitative result, they would not provide an accurate quantification of concentration or emission rate.

Another colorimetric indicator dye is in development that can be applied as a coating to pipelines or as a pigment in clothing [49]. This indicator reacts within 5-10 seconds of exposure to hydrogen, allowing the development of fast response, wearable safety indicators for workers on hydrogen infrastructure. This technology is still in the research stage, with a low TRL, but it presents an interesting opportunity for further development.

3.2.4 Sensor networks and distributed sampling

NPL's Fugitive Emissions Detection System (FEDS) [51] can provide long term near-continuous coverage of a site – for methane. However, its spatial coverage is limited due to the logistical challenges of deploying tubes across a site and the due to technical constraints of the current system the tube lengths between sampling point and analyser are limited to 300m. Currently, further work is required to understand the scope, feasibility and sampling strategy of such as system for hydrogen (e.g. sampling inlet placement).

Currently there are no validated methods based on lower cost sensors that can survey (detect and localise) emissions and quantify hydrogen emissions over a large area and provide continuous time coverage.

There are sensor-based technologies available for the detection hydrogen [18] within portable (handheld) instruments, but further work is required to understand their feasibility and scope for inclusion in a wider range of applications (e.g. networks to cover large areas and/or provide a continuous monitoring capability). Such work would include:

- To understand the transport of hydrogen across a wide area that could inform sampling strategies (e.g. where to place sensors) and whether such networks could meet intended purpose.
- Investigation of modelling techniques to estimate emissions rate from the concentration measured by the sensor.
- Laboratory tests to understand sensor behaviours under a range of conditions.
- A means to validate sensor networks.

Two examples of technologies that could be incorporated into sensor networks are: optical fibre based sensors and micro-electronic-mechanical systems.

Micro-Electro-Mechanical Systems (MEMS)

Several examples can be found in the literature of efforts to develop mechanical sensors [52], such as the Micro-Electro-Mechanical Systems (MEMS) using microcantilevers for hydrogen detection at sub ppm concentrations in laboratory-controlled conditions [53].

Nevada Nano offers devices with multiple complementary chemical sensors on a single Si chip, called Molecular Property Spectrometers (MPS™) [54]. This is an example of a MEMS sensor, made by an array of micro-cantilevers. The manufacturer claims that this gas sensor measures a variety of properties of sampled vapours, liquids, and particles, then a custom software identifies the types of molecules present in an unknown sample. As these are commercially available, the technology has been assigned a TRL of 9+. Furthermore, they comment that the sensor will be able to quantify fugitive emissions, but no sampling method is mentioned besides the detection and the concentration measurement capabilities.

National Gas have been undertaking trials with a Nevada Nano MEMS sensor to continuously monitor fugitive emissions from methane at a compressor site in the UK, they have also been deployed at the DNV test site in Spadeadam for hydrogen monitoring. National Gas gave a presentation at the Gas Analysis symposium (Paris) in January 2026.

It is anticipated that this could be designed as a technique for continuous monitoring or sensor technology used in a handheld portable technique.

Fibre optic based sensors

The traditional optical fibre sensor is an intricate assembly of several components: a light source, an optical spectrum analyzer, the actual optical fibre, and a coupler. By attaching a hydrogen-sensitive material to the fibre, reactions with the gas can induce optical material property change, altering light properties that can be analysed to measure the concentration of hydrogen [55].

Fibre optic systems offer the advantage of remote operation capability, and demonstrate several beneficial characteristics including long-term stability, high sensitivity to hydrogen, and straightforward operating mechanisms. Also, optical fibres can be distributed across a site to create a large detection network. While optical fibres don't act as remote sensors, a distributed network of connected sensors offers similar benefits. The sensing components of a fibre optic system contain no electrical components, making them intrinsically safe for operation in explosive hydrogen.

Most fibre optic detection technology is in the development stage, with a TRL of 4 to 6. Research is being done into improving a wide range of optical fibre detection techniques, including interferometer technology, Surface Plasma Resonance (SPR) technology, micro lens technology, evanescent field technology, integrated optical waveguide technology, and direct transmission/reflection detection technology [56].

Two examples of commercially available fibre optic hydrogen sensors are the United Fiber Sensing hydrogen leak detector [57], and the Technica T910/FBG hydrogen detection sensor [58], both of which use Fibre Bragg Grating (FBG) technology. These sensors have daisy-chaining capability, for easy integration into fibre optic systems, and have measurement ranges of 0.1 – 100 vol% and 0 – 4 vol% hydrogen in air respectively.

The EU Optic Fibre-based Hydrogen Control Systems (OPTHYCS) [59] consortium are projects aimed at developing sensor technologies for continuous leak detectors based on optical fibre technology, the advantage is that this technology can be deployed in hazardous and remote areas and potentially provide continuous monitoring capabilities covering large areas.

It is anticipated that this could be designed as technique for continuous monitoring.

3.2.5 Bagging

Bagging is defined as a means to quantify mass emissions from equipment (component) leaks in the Environment Protection Agency (EPA) protocol for Equipment Leak Emission Estimates [60]. This protocol defines two bagging approaches: a vacuum and a blow-through technique. In both techniques, the emission rate from a component is measured by sampling a leak using a container constructed from an impermeable, antistatic and inert material and then evacuating the undiluted leak from the container at a constant measured flow rate. This sample is then analysed using a sensitive and accurate method (such as Flame Ionisation Detector (FID) in the case of NG or Mass Spectrometry in the case of hydrogen). Also, this technique can be applied in the field using a sniffer detector (also called a leak detector), although the method needs to be adapted for hydrogen leaks rates at industrial scale (in the order of litres per minute). Some applications include using a reference leak EN ISO 20485:2018 [61] although these are focused to relatively small leak rates (typically in the order of 10-5 to 10-3 litres per minute). In fact, the above-mentioned standard is focused on leak testing of medical devices, and it can be applied to other analytical or lab-based instruments, but it is not foreseen the development of reference leaks for industrial leak uses. The techniques differ in how the sample is conveyed through the container. In the vacuum technique, a pump is used to pull air through; in the blow-through technique, the sample is blown into the container. As far as the authors are aware there is no available method that has been validated for hydrogen emissions. This is a ‘snap-shot’ and portable technique.

3.2.6 Potential use of techniques for filling capability gaps

The techniques highlighted could be considered to fulfil the technological and methodological gaps identified in Section 2 (refer to the summary in Section 2).

However, their suitability will depend on the instrument performance criteria defined in the method, the characteristics of the emission source and how the method is performed (e.g. sampling strategy). A test and validation campaign will be required to assess potential techniques. Table 4 is a list of potential uses for these techniques.

Table 4. Potential uses of techniques.

Technique	**Potential use**
Foaming solutions	To help validate the existence of a leak
Colourmetric	
Sensor network (e.g. Fibre optic sensors)	Continuous detection monitoring - covering large areas such as pipelines and inaccessible (for handheld monitoring) areas.
Sensor network (e.g Micro-Electro-Mechanical Systems)	Continuous detection monitoring - covering large areas such as pipelines and inaccessible (for handheld monitoring) areas.
OGI with tracer	Snapshot measurements of parts of the hydrogen value chain that could be purged, pressurised with a tracer gas, for example storage tanks.
Bagging	Snap shot quantification measurement or validation of calculated emissions from vents or ducted emissions. Quantification of emissions where high flow is not possible (e.g. ATEX)
Acoustic Cameras	For continuous monitoring of selected areas.

Table 5 shows a comparison of the techniques described in section 3, showing their scope, whether remote sensing (useful for monitoring physically inaccessible areas) and readiness.

Table 5. Shows a comparison of the techniques described in section 3, showing their scope, whether remote sensing (useful for monitoring physically inaccessible areas) and readiness.

Technique	Scale		Detection or Quantification	Remote sensing	Readiness
	Spatial	Temporal			
Sniffer and passive sensor	Component	Snapshot	Detection	N	Method development Under NHyRA
Acoustic Camera			Detection	Y	
High flow sampler			Quantification	N	
Foaming solution			Detection	N	COTS
OGI with tracer			Detection	Y	Emerging
Bagging			Quantification	N	Emerging
Colour metric			Detection	N	COTS
Sensor networks	Component, Functional element or Site	Continuous	Detection or Quantification	*	Emerging
Acoustic Camera	Component	Continuous	Detection	Y	Emerging

*depends on implementation. COT = Commercial Off The Shelf.

4. Workshop

This section describes the objectives and outcomes (summary) from a workshop that was held on 2nd December 2025 between National Physical Laboratory, Government (Environment Agency (EA) and Department of Energy Security and Net Zero (DESNZ)) and representatives from industry (consisting of instrument manufacturers, mobility, research, energy suppliers) and a UK hydrogen trade association. Detailed notes taken during the workshop are in Annex 2.

4.1 Objectives and scope

The purpose of the workshop was to understand the key challenges and barriers for implementing LDAR and MCERTS for hydrogen detection and quantification at component level. The workshop provided an opportunity for the UK's National Measurement Institute (NPL), government representatives, instrument suppliers and the hydrogen industry (from production, transport to end use) to gain insight into the measurement needs, current and future hydrogen measurement capabilities and methods, and to help define priorities for the future. The focus was on hydrogen production and associated activities (e.g. storage, vents, flaring etc).

The workshop consisted of three scene setting presentations followed by targeted discussions. Table 6 is a list of attendees, organisation and area of expertise.

Table 6. Workshop attendees

Organisation	Attendees	Expertise / Area
National Physical Laboratory	9	Emissions metrology, covering pollutants, greenhouse gases (including methane), hydrogen; method development, test and validation; standardisation; NHyRA consortium member leading the test and validation of measurement based methods.

Organisation	Attendees	Expertise / Area
Environment Agency	6	Technical advisors, installations officer, national permitting service, chair of EH2/1 (stationary sources)
DESNZ	1	Policy advisor
Instrument manufacturers	2	Sensors, acoustic cameras
Network Operators	1	Hydrogen and CCUS
End user (automotive industry)	1	Industry representative
Hydrogen Energy Association	1	Policy analyst
R+D institute	2	NHyRA consortium member, leading the development of measurement and calculation based methods
Energy supplier	2	NHyRA consortium member

4.2 Presentations

The following scene setting presentations were given:

1. The hydrogen landscape from a metrology perspective and an overview of NPL's hydrogen test and validation capabilities.

   The first presentation from NPL described the reasons why hydrogen should be monitored (safety, environmental, energy security and efficiency); the types of monitoring (including detection to locate leaks to quantification to provide evidence data to make informed decisions); the different types of emissions sources (fugitive, vented and sources of combustion) and different monitoring techniques. The

presentation highlighted current work within the hydrogen space (e.g. NHyRA [19]) and an overview of NPL's testing and validation activities and facilities.

The challenges associated with implementing monitoring are:

- The costs associated with a LDAR programme.
- The limited commercially available products (especially instruments that are approved to operate in explosive environments, e.g. ATEX).
- The need for knowledge and experience into the behaviour of instruments with hydrogen to develop best practice. This is an evolving area, more mature for methane, there should be many aspects that can be learnt and potentially implemented from NG or methane monitoring.

2. The hydrogen landscape from a regulator's perspective

   The second presentation from the EA provided an overview on background of the project that has instigated this report and its timeline, a summary of the EAs MCERTS programme outlining the benefits of the scheme, its scope and structure and what an MCERTS for fugitive emissions would consist of.

   One challenge is determining realistic performance criteria that meet regulatory requirements and the purpose of the monitoring. For example, the HEMS [44] scheme is for landfill gas boreholes and low risk combustion plants, so has less demanding performance criteria than the scheme for portable instruments used to calibrate Continuous Emission Monitoring System (CEMS) on large industrial plants.

   When it comes to applying standards some operators may prefer a 'tick-box' approach while others would prefer the information that comes with quantification as that can provide the valuable evidence data to help determine what is fit for purpose and cost effective in terms of monitoring, quantification provides information that allows appropriate rules to be set.

3. The third presentation from Distran (manufacturer of acoustic cameras) provided an oversight on experiences using these types of instruments. Currently most cameras deployed are for safety monitoring. Such cameras allow for investigation of out of

reach components but there are limitations where they can be deployed, for example insulated pipes can disrupt the acoustic energy generated by a leak, therefore limiting the ability of a camera to detect the leak. Cameras can have features for leak quantification. Leak rate is not necessarily proportional to the acoustic intensity measured by the camera, there are many factors to consider (such as pipe lagging that can block sound, pipe material etc), in order to accurately quantify a leak. Acoustic cameras could have a place as a complementary method to sniffing based techniques and alternative to Optical Gas Imaging (OGI) which is used for Natural Gas (NG) and methane. Considerations for the development for standards are that it's difficult to determine a detection limit (as there are many factors that determine the measurement) and defining a method of calibration based on known concentrations.

4.3 Workshop summary

The workshop explored the practical insights and challenges for monitoring hydrogen emissions across the value chain, focusing on leak detection and quantification covering the following themes as targeted questions:

- Theme 1: Practical insights and challenges with hydrogen monitoring
  - Q1: How practical are current techniques for monitoring hydrogen? Challenges from an instrument and implementation perspective.
  - Q2: What types of emission sources are relevant?
  - Q3: Anything from methane landscape that can be applied to hydrogen?
- Theme 2: Developing a framework for LDAR and MCERTS.
  - Q1: Are there best practice guides (not standards) that would be useful?
  - Q2: What guidance do instrument suppliers need?
  - Q3: What training and competencies are needed?
  - Q4: How will schemes scale up in the future?
  - Q5: What are the measurement needs from a metrology perspective?

The key discussion points have been categorised as follows: data needs, documentation needs, monitoring methods, research needs, instrumentation, limitations and barriers, engagement with industry (value chain), engagement with instrument manufacturers and other observations. The following provides a summary of the discussion points:

Data needs:

- Data is needed to provide the necessary evidence to support and defend any decisions made (permitting, regulations, policy advice etc).
- There is a need for more data to be collected from operating sites to provide a clearer picture of what the current emissions are (i.e. amount emitted and their characteristics) from different sites and from a diversity of processes and components.
- To determine what particular types of (arrangements) of components leak the most (if any), so that a LDAR measurement campaign can be focussed on those components.
- Are there emissions from specific components that should be modelled to better understand leak behaviour?
- Observe how emissions will evolve in the future, including trends to see how sites are improving.
- Collecting data will provide an opportunity to gain further experience of using methods and instruments.
- Data to determine how often should a site be checked, i.e. LDAR frequency.
- Data to gain a better understanding of leak thresholds, for example for different monitoring purposes: environmental, efficiency and pre-emptive safety. Devise appropriate leak thresholds (i.e. what constitutes a leak), should be periodically reviewed based on evidence data. To understand what needs to be reported for permitting considering keeping a site safe, efficient and to protect the climate.
- Data for vented and sources of combustion as well as fugitive.
- Data to help determine decisions on whether to undertake flaring verses releasing verses capturing hydrogen.
- A means of logging and sharing data (for accumulating evidence data). What predictive tools could be used? How else can evidence data be shared? Could the NHyRA emissions database be used [62]? Lessons learnt from NHyRA in terms of building and populating this database.
- Start to build emissions factors for types of processes (at what granularity could this be achieved and be useful, e.g. process / functional element level or site level).

Documentation needs:

- Generalised guidance documents and best practice documents, key is flexibility and not being too specific. For example, a training manual (best practice guide) to allow sites to conduct monitoring for themselves.
- Guidance documents, best practice guides and standards need to be clear on their scope (and limitations).
- Guidance and best practice guides could offer a quicker route to adoption compared to standards, also they could be used as a precursor to standards, obtaining evidence and feedback during their use, to help ensure that standards developed are fit for purpose. Consider following methane pathway to developing standards, basing information on existing standards can help with early adoption.
- There needs to engagement (with industry) in the creation of guidance documents, best practice guides and standards (see below).
- An example of an existing good practice guide is on the maximum admissible leaks (i.e. the lowest emission that triggers action) in hydrogen and hydrogen-enriched NG pipelines There is a good practice guide [63]. The purpose of the guide is to review the requirements and existing metrology infrastructure for the calibration and traceability of portable hydrogen leak detectors.

Monitoring Methods:

- Measurement-based methods are needed to validate engineering calculations or assumptions made regarding vented emissions, cover episodic sources and understand emissions from combustion (e.g. slip), these could be based on existing techniques such as sniffers or bagging.
- Methods to monitor fugitive emissions (at component) level are being developed and validated (under NHyRA) using commercially available instruments (for leak detection) and for leak quantification a Bacharach Hi Flow® that has been adapted by NPL to use a commercially available hydrogen detector.
- For the methods being developed for NHyRA, to gain an understanding of their ability to meet the measurement needs. Are there gaps in their performance and scope that that need to be addressed? For example, does the high flow have sufficient sensitivity and is its physical coverage (considering inaccessible areas and the need to physically couple to the leak). Do additional (complimentary)

methods need to be developed to cover missed areas (such as physically inaccessible areas) and is there a need for continuous measurement?

- An understanding of capability and technology gaps are needed to address these limitations and engagement with instruments suppliers to encourage innovation. Also, LDAR schemes may be costly to operate.

Research needs:

- Research on the dispersion properties of hydrogen which could inform on the feasibility, scope and sampling strategy of techniques that monitor at distance (i.e. to monitor physically inaccessible areas).
- Research on odorants - impact on instruments, can they be used as a tracer?

Instrumentation:

- More user experience to understand the limitations of the various techniques for monitoring hydrogen, in particular acoustic cameras. This links to the need for evidence data (see above). Need to understand instrument scope and limitations, their niche and how different instruments or techniques could be used to complement each other.
- What role can non ATEX or prototype systems have, a need to understand the level of risk that is acceptable. Safety must always be imbedded in methods.
- An understanding of the capability / technology gaps (e.g. the need for continuous monitoring).
- There needs to be engagement with manufacturers so they can better understand what the instrument needs are. Manufacturers must address uncertainties to build confidence in data.

Limitations and barriers:

- Sniffers and high flow – physically inaccessible areas and high flow needs good coupling to the leaking component.
- Cost of ATEX approval for instruments.
- Costs and pushback from operators – may prefer a tick box approach rather than collecting evidence data.

Engagement with industry (value chain):

- How are systems approved for use in the hydrogen value chain? Need to understand the monitoring needs of purpose built and adapted sites.
- How do operators respond to leaks (safety, economic and environmental). Is there any synergy with Health and Safety Executive (HSE), i.e. spotting leaks well before they become a safety issue.
- Could economic (efficiency be used as a leverage for monitoring)? For this we need evidence data, i.e. what level of detail (e.g. detection thresholds, spatial an temporal scale) is needed to understand the balance cost v's benefit.
- Engage with industry (e.g. JCB, Toyota and AVL) regarding emissions from combustion, what needs to be done in this area?
- Engagement needed for developing best practice and guidance documents.

Engagement with instrument manufacturers:

- Awareness of the challenges and needs for monitoring, for manufacturers. What do they need to know next / on the horizon?
- Consider the product certification scheme to help products into market and confidence using products.

Other observations:

- Scaling up in the future. Use of data sharing tools to pool data (may need to be anonymous to retain confidentiality). We need broad, general policies that can cover a shifting gas landscape. Scaling is really about flexibility.
- There needs to be an incentive for sites to monitor emissions, for example to provide data to help improve operational efficiency.
- Monitoring of non-hydrogen emissions and their impact.

Overall, there is the urgent need for evidence-based guidance, stakeholder engagement, and flexible monitoring frameworks to enable cost-effective, reliable hydrogen emissions monitoring.

5. Summary and next steps

5.1 Summary

This subsection provides a summary of the work carried out (as described in sections 2 and 3 of this report) to address the objectives defined in section 1.3:

- It is predicted that hydrogen production sites will scale up over the next 10 years, there are currently several sites in operation in the UK and approximately 200 projects to develop sites, mostly small electrolysis or gas reforming / gasification-based sites. The monitoring of many sites using handheld methods could pose challenges in terms of cost depending on the LDAR frequency.
- Monitoring requirements (e.g. how a LDAR and MCERTS schemes are implemented) should consider the details of the emissions source (e.g. temporal nature of emissions) and the data reporting requirements (e.g. the need for quantification and uncertainties).
- Data is needed to define LDAR requirements such as: monitoring frequency, what magnitude of emission should be considered a leak and prioritisation (e.g. types of components or processes where most leaks occur). Quantification is encouraged since it can be difficult to assess emissions based on concentration alone.
- Implementing a LDAR scheme soon (i.e. next 3 to 5 years) could be based on the methods currently being developed and validated under the NHyRA project. These are:
  - A leak detection method using sniffer and passive sensor instruments complimented with the use of acoustic cameras.
  - A leak quantification method using the high flow sampler.

  The scope of these methods is the monitoring of fugitive hydrogen emissions component spatial level and snapshot / periodic monitoring using handheld portable instruments.
- The key challenges associated with these methods are that physical accessibility near the component to be inspected is needed and they only provide a snapshot measurement in time. For quantification using the high flow sampler capturing the full emissions plume is necessary to accurately quantify leaks. Acoustic cameras

are still an emerging technology, guidance is needed on their use, currently they are an indicative technique that could compliment sniffers.

- If only these methods were implemented then there are the following monitoring capability gaps that will need to be addressed, the need for: continuous monitoring, remote quantification and improvement in instrument performance (i.e. to have sensitivity below approx. 10ppm, less susceptibility to interfering gases including humidity and further testing against preferential emissions, e.g. hydrogen enriched NG). Further guidance on the use of emerging techniques such as acoustic cameras are needed.
- MCERTS has three elements: product, personnel and organisation certification. For the methods in development (sniffer, passive sensors and high flow sampler) the use of EN 15267 could be considered for performance assessment as part of an MCERTS scheme.
- The methods being developed and validated under NHyRA are based on an existing standard (EN 15446) which should facilitate submission to a standards body (such as the BSI) and their widespread adoption by industry.
- The development of monitoring techniques and methods that fall out of the scope of this work are needed:
  - The development of validated methods that operate at wider spatial scales (functional element to site level) could monitor physically inaccessible areas (if a remote sensing technique), diffused emissions from multiple sources, as well as potentially cover sites more efficiently to screen a site for emissions and obtain as site emissions total. However, further work is needed to understand the transport of hydrogen over large areas so that their scope, feasibility and sampling strategy of large area techniques can be assessed.
  - The development of validated methods to cover emissions from vents and sources of combustion.

5.2 Next steps: Development of MCERTS and LDAR standards at component scale

To develop LDAR and MCERTS standards within the scope of this work, i.e. detection and quantification at component scale, the following next steps are recommended, building on the methods currently being developed and validated under NHyRA [21]:

5.2.1 Data

Validated standard methods that quantify emissions are needed (to provide tools for acquiring the evidence data) and an understanding of their uncertainties (and required instrument performance).

To gain evidence data and experience of using instruments, the following steps are suggested:

- To develop a measurement campaign plan to undertake measurement campaigns at production facilities to address the needs listed above. The choice of sites should be based on a priority list based on:
  - Physical accessibility, geographical location and willingness of operators to accommodate measurements.
  - Type of site, e.g. purpose built for hydrogen or repurposed.
  - Technical and scientific value, i.e. which data needs (see above) need to be prioritised?
  - Cost of undertaking the measurements. The initial target should be to repeat the measurements after 1 year to understand changes over time.

- It will be important to collate costs of equipment and effort to undertake the campaigns and to understand the economic value of repairing leaks (from different types of components) and leak rates.
- Examples of evidence data are: identify specific component types or processes that leak the most and what level of emission constitutes a leak.

Questions with regard to obtaining and sharing this evidence data:

- How are data and experiences to be shared?
  The NHyRA project is designing and developing a database for hydrogen emissions (covering fugitive, vented and sources of combustion), throughout the hydrogen value chain. This aim of the database is to provide a reliable source data on hydrogen emissions, obtained from measurements, validated calculations and peer reviewed data. In view of collating evidence data, use of this database should be considered.
- Should case studies be written?
- What competencies are needed to undertake campaigns?
- A means to collect data is to make data collection a requirement for permitting – an action is to consider how best to achieve this.

5.2.2 Documentation

Development of best practice and guidance documents.

- Further guidance on the use of acoustic cameras and their limitations, the content on this can be based on experience from previous or future campaigns. (*an output from the proposed measurement campaigns – see above*).
- Guidance on what data to report based on monitoring purpose and characteristics of the emissions source, that could supplement the low carbon hydrogen standard.
- Generic guidance: how to undertake a monitoring campaign; current technologies that are available, their scope and limitations; how to monitor different components; stakeholders to approach for different needs and stakeholders obligations (e.g. site operator).
- Develop a draft EN 15267 part 4 for sniffers and passive sensors and high flow and review the competencies required for these techniques.

5.2.3 Engagement

- To explore the possibility of a joint industry and regulator working group.
- To compile a targeted questionnaire for industry, to help answer the questions under the ‘engagement with industry’ sub section above; engagement could be via

relevant trade bodies such as the Hydrogen Energy Association (HEA) or Hydrogen UK.

- Engagement with end users regarding combustion – what are the challenges?
- Engagement with instrument manufacturers to understand barriers to market, what is it they need to know.
- There needs to be a plan on how to regulate existing sites that currently vent hydrogen.

5.3 Next steps: Development of methods to fulfil capability gaps and beyond scope of this work

This section defines the next steps to address the capability gas and extend the scope of monitoring methods:

- There is a need for continuous measurement as this could ensure that emissions events are not missed and may be a cost-effective alternative to monitoring using handheld instruments. Optical fibre and MEMS based sensors (currently being trailed by National Gas at Bacton) are examples that may have a role - particularly surveillance and detection. *(NPL to liaise with National Gas on their use of the Navada Nano MEMS sensor – to investigate further testing and to understand their scope. NPL to reach out to OPTHYCS consortium to investigate whether optical fibre sensors could have a role to play).*
- Estimation of emissions calculation-based techniques (and their validation) is an area that is being addressed by NHyRA.
- To write a road map on how remote techniques for hydrogen detection and quantification should be developed and development of techniques that can measure at functional element and site level. The type of work to undertake this would be, for example: to develop a better understanding the dispersion of hydrogen over scales; undertake testing using new technologies such as MEMS, fibre optic and existing techniques such as bagging to better understand their scope and performance; development of Raman (remote sensing method).
- It is important that methods are tested, validated (including an understanding of how uncertainties are derived and traceable to primary gas standards). Also, an understanding of the conditions during validation and the scope of the method are

important. Validation should include laboratory and control release testing (NPL has facilities described in Annex 1) and at representative sites.

6. Conclusions

Evidence data on emissions and their characteristics, from different types of production sites and ranges of components are much needed to help support decisions that need to be made in answering questions such as: what is the most cost effective LDAR frequency, are there specific component types to focus on, what level of emission constitutes a leak, what are the associated costs? Are there different thresholds depending on the purpose of the monitoring (i.e. pre-emptive safety screening, minimising product losses and to protect the environment)? Can future emissions be better predicted using the evidence data?

There is a need for guidance documentation, in particular the use and testing of emerging techniques such as acoustic cameras and novel sensors. There is also a need for generic guidance on how to conduct a measurement or leak detection campaign, what are the best techniques to deploy and what data should be reported for a given monitoring need. There are no MCERTS standards covering fugitive emissions of hydrogen, one route is to develop a new standard based on EN 15267 part 4 for sniffers and passive sensors and high flow based samplers. A method verification roadmap for emerging techniques would be valuable, for example identifying what is the best approach for ensuring the competency and performance of acoustic cameras.

Validated methods are being developed and validated to detect and quantify emissions at component level under the NHyRA project. These methods use handheld instruments to detect and quantify emissions at component level. This report has highlighted capability gaps for monitoring: that is the need for continuous monitoring (there are merging techniques that could be promising), to monitor over large areas including remotely that could cover physically inaccessible areas. This is an area of ongoing research.

Can emissions reporting be used to improve efficiency of sites and pre-empt safety issues to incentivise monitoring? Further engagement is needed with industry to understand their needs, their response to leaks and to have a better understanding of emissions from sources of combustion. There needs to engagement with industry on how best to get

instruments to market, overcome barriers about product certification and could there be a role for prototype equipment?

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Annex

Annex 1: NPL's test facilities

Laboratory testing facilities

The Environmental Emissions Metrology Group at NPL has developed laboratory test facilities and associated expertise for hydrogen measurement instrumentation over the past 5 years. This has included the development of specific test capability to systematically test instrumentation and associated methods of use for detection of hydrogen releases, concentration measurement and leak rate measurement. Associated safety protocols have also been established to enable testing with hydrogen in the flammable range so that tests requiring this can be conducted if required.

Creation of reference emissions using HCRF

The Environmental Emissions Metrology Group at NPL currently operates Controlled Release Facilities (CRF) – systems which can be used to create reference emissions of different gases to replicate fugitive emissions for the purpose of test and evaluation of monitoring methods. Under a Government Office for Technology Transfer (GoTT) funded project, a CRF was developed specifically for hydrogen (HCRF), which allows for the creation of metrologically traceable hydrogen release rates between 0.005 and 50 L/min (0.027 - 270 g/h) with defined measurement uncertainty, typically ≤5% of rate (95% confidence). These controlled emissions can be used to test the performance of hydrogen detection and quantification methods under real world representative conditions and establish key metrics such as Limit of Detection (LoD), Limit of Quantification (LoQ) and sampling efficacy. Figure 9 shows a photo of the CRF.

Figure 9. Controlled release facility

Annex 2: Workshop discussion notes

The workshop discussions were focussed on the following themes and questions:

Theme 1: Practical insights and challenges with hydrogen monitoring

Q1: How practical are current techniques for monitoring hydrogen? Challenges from an instrument and implementation perspective.

Instruments

- There is no “one size fits all” in terms of matching the capabilities of techniques or instruments to data reporting requirements and the various types of emission sources. It’s important to understand their scope (e.g. physical magnitude to be measured, detection or quantification, limitations and any assumptions that are made) and how to implement them and their technology readiness. An appreciation of how different techniques could complement each other is important.
- Instruments (particularly acoustic cameras), more experience of using them is needed to better understand their limitations and therefore develop the appropriate guidance on their use so they can be fit for purpose.
- Authorisation on the use of non-ATEX (e.g. prototypes) on sites. It could potentially be difficult to convince operators to use these types of instruments. Need to understand what level of risk is appropriate for monitoring using Non-ATEX instruments and where they can be used on sites.
- Instrument manufacturers need to address uncertainties for their instruments – as that provides a measure of confidence in the data provided.
- Methods are being developed (by NHyRA) using portable (walkover survey) instruments. Their scope (sniffers and high flow) will be limited to physically accessible areas. LDAR schemes could potentially be costly (depending on size and frequency of surveys) and intermittent emissions sources maybe missed. For methane there are many options that should be considered for hydrogen, such as a using fixed network of sensors, point sampling using a vehicle (if appropriate).

Hydrogen value chain – systems and processes

- Hydrogen vehicles are purpose built and engineered to avoid leaks and have very basic leak detection systems; if a leak is found, typically no specific information is given, and the whole system is shut down.
- There are some questions for industry and operators:
  - Regarding hydrogen vehicles, under what circumstances might this shut down philosophy be suitable?
  - How are systems approved for use in the hydrogen value chain (highlighting differences between purpose built and adapted sites)?
  - What is the difference between purpose-built sites and adapted sites (for hydrogen) – in terms monitoring needs?
  - It is expected that there will be a higher number of leaks in adapted sites.
  - How do operators at sites respond to a leak?
  - How are systems (infrastructure) approved on a site.
- Consider populating a questionnaire to industry and operators.

Monitoring: Incentive and costs

- The costs of implementing a LDAR scheme, especially for smaller sites which are less efficient (in terms of hydrogen released per hydrogen produced) could be an issue for operators. Evidence data is needed to determine what is reasonable in terms of the frequency of LDAR monitoring based on the size of a site. A suggestion is to conduct a trail at one or more sites.
- A commercial incentive for conducting fugitive emissions monitoring should be considered. To achieve this there is a need to understand the cost of undertaking a LDAR campaign verses the efficiency savings that could be obtained by conducting a LDAR campaign to repair leaks (that are not large enough to be a safety concern). Perhaps identify different reporting thresholds for safety, efficiency and the environment.
- Monitoring might involve some sort of enforcement, e.g. “spot check” visits to sites, test their facilities. The outcomes could be quantified in levels of severity. Such a need could be met using a scheme similar to the Common Incident Classification Scheme [64], for example to record incidents of landfill gas exceeding a threshold.

- Therefore, there is a need to determine the level of emissions in terms of type of sources and the amount of hydrogen emitted. What is considered a leak? Will this be defined differently depending on the monitoring purpose (i.e. safety, environmental or economic)?
- There is a need to address limit of detection thresholds, on what basis would this apply? Need to define a threshold that is appropriate, potentially based on type of facility, process or configuration of components.

Quantification

- There is currently no evidence data to set appropriate requirements for monitoring that is cost effective. What would the frequency of monitoring be? Evidence is needed to defend any requirements set.
- Currently there is no guidance on what to report, how detailed the data is, how do we report it, and who is trustworthy do to the measurements.
- Emission factors (at functional element and site level, challenging to apply at component level) - currently there is no data to calculate emission factors, so these can't be applied at the moment.
  Note: Emission factors would probably only be meaningful at functional element (spatial level), i.e. complete process units, tanks etc rather than individual units.
- Quantified emissions is needed to build evidence data to be able to set requirements that are appropriate, fair and fit for purpose, and to understand impact of different types of emissions. This requires access to sites to collect data. One solution to this may be to make allowing data collection a requirement for permitting, an action is to consider how best to achieve this.
- Could consider quantification on an annual basis how much hydrogen is released per hydrogen produced – would provide an indication on the efficiency of the process. Low carbon hydrogen standard, criteria is < 20 g CO_2 e/MJ hydrogen product, but currently this does not include fugitive hydrogen emissions but may in the future in which case the criteria may need to be reviewed. Liaison and aligning interim requirements have been initiated by EA. Currently operators need appropriate (i.e. cost effective and low uncertainty) monitoring methods to determine the impact of emissions (fugitive) on this target.

- Need evidence data on how much hydrogen is emitted each year and build up a trend over years to see whether sites are improving, but what uncertainty is needed? If fugitive emissions are seen to be under control, then there may be less need to monitor.
- How to define a leak rate threshold? Currently leaks that are not a safety risk are not reported and assumed negligible. Thresholds could be set based on:
  - The method's limit of detection.
  - Acceptable product loss (efficiency), could a repair be deferred or is more urgent action needed?
  - To pre-empt a safety issue.

  There is a need to understand limits for safety, product loss and environment.

- The need for more data means that there is a need to physically access sites to collect data, this could be addressed by requiring that data collection (quantification) is part of the permitting process. However, allowing researchers (with prototype instruments) on site to collect data may prove challenging. There is a need to state a minimum frequency (to perform a LDAR campaign) to collect data. Initial issues with costs of collecting data which may reduce over time.

Q2: What types of emission sources are relevant?

- Vented emissions are generally considered to be brief in time but higher in mass emissions compared to fugitive emissions which are lower in mass emissions but long term. Both types of emissions will contribute to a site total. Need the evidence data to understand their impact on site efficiency and the environment.
- Fugitive emissions monitoring methods are currently under development (NHyRA). Currently, undertaking fugitive monitoring is more feasible as its more developed (using commercially available instruments) whereas measurement-based methods for vented and sources of combustion are not currently being addressed within the NHyRA project, although calculation-based methods are. The project is developing empirical calculations and using CFD modelling (which can be validated using measurements) for emission type and component scenarios where deploying measurement-based methods may not be cost effective, for example fugitive

emissions from an underground pipe and purging. The emission rate is calculated from the product of the emission factor and an activity factor.

- Venting has been considered less of a priority (in terms of developing measurement-based methods) since estimates of emissions can be calculated if the relevant engineering parameters are known. Combustion sources are more of an unknown (e.g. slip). However, measurement-based methods are needed to validate calculations or assumptions made (e.g. any operator stated efficiencies), estimate emissions from the type of vents that can't be reliably undertaken using calculations (e.g. episodic emissions) and to understand sources such as slip from combustion.
- Does hydrogen slip have an impact on the environment and site efficiency? Manufacturers such as JCB and Toyota are developing hydrogen fuel combustion engines. An action to approach engine manufacturers for their experiences and whether monitoring slip is needed for efficiency purposes.
- There is some discrepancy with regard to some existing sites being permitted to vent hydrogen and new sites – that needs to be addressed. Existing chlor-alkali sites and other permitted sites may have historic hydrogen venting before hydrogen was known to be an indirect GHG. The low carbon hydrogen standard was designed with the knowledge that hydrogen is an indirect GHG as are any new permits for hydrogen production. There are requirements within this standard for fugitive hydrogen monitoring and reporting (the term 'fugitive' in this standard includes venting). Action: there needs to be a plan to regulate these existing sites. How can this be retrospectively addressed? There needs to be the evidence to support this.
- Need to consider monitoring of other (non-hydrogen) emissions from the hydrogen value chain:
  - Potential for emissions of ammonia. Ammonia is being considered as a means of transporting hydrogen; consisting of hydrogen to ammonia conversion, handling, storage and transport of ammonia and the reconversion process back to hydrogen.
  - Proton exchange fuel cells typically use membranes containing PFAS [65]. PFAS emissions could emanate from activities such as venting (e.g. purging) and may therefore need to be monitored.

Can vented hydrogen be used? In some processes hydrogen that is vented may be a waste product. Depends on process if it can be captured. Need to consider whether it better to vent or flare in terms of impact on the environment. Need to understand the trade-off between environmental costs of hydrogen as an indirect GHG and emissions of NOx from burning. There may be a limit (an emissions rate threshold) below which where venting is the best option, or upper limit to recover or flare.

Q3: Anything from methane landscape that can be applied to hydrogen?

- NPL are currently gathering evidence (under NHyRA and NPL-DESNZ projects) on the monitoring of fugitive hydrogen to understand these differences between methane/natural gas and hydrogen fugitive monitoring. It has been observed that hydrogen leaks are challenging to locate (density of components, “pooling” of plumes in still environments) and how to deal with false positives.
- The design of a sampling strategy (when and where to take measurements) will need to be based on the monitoring techniques, for example for acoustic cameras, it was suggested to separate monitoring between low and high-pressure scenarios.
- Consider following methane pathway to standards, starting with detecting fugitive emissions, then applying emissions factors to sites or processes before trying to quantify fugitive emissions, however there is currently not enough data to base emissions factors on.
- Historically thresholds for a leak in methane LDAR has fallen over time.
- What is the difference between hydrogen and methane emissions (in terms of the number of leaks observed), it is significant? For large leaks (large flow), this difference not likely to be significant, but for leaks from a defect (e.g. loose flange) or through a material (much more permeable) it will probably be more significant for hydrogen. More detailed work (evidence data) needed here to understand these differences.
- What are the comparable technologies, which gaps are being filled and how easily?
- Difference in that there’s not a huge market for hydrogen. For equivalent leak detection, sniffers should be sufficient.
- What we’ve learned so far - involve *all* stakeholders; make sure we have regulations (or some mechanism in place) to present before trying to implement a

LDAR scheme. Need to consider what the future hydrogen economy will look like – that will really affect the actions/type of monitoring that's needed.

- Creating demand for instruments. If emission reporting is required, then default values are used where measurements are not available (e.g. flare is 98% efficient). If an operator can show, through measurement, that their emissions are lower than the default then they can report a lower value (which could have some associated benefit to them). This could then create demand for measurement techniques from industry and help to overcome the technology gap which currently exists.

Theme 2: Developing a framework for LDAR and MCERTS

Q1: Are there best practice guides (not standards) that would be useful?

- It is important to define required (safety) certifications to be included in guidance documents as safety is embedded into monitoring activities. There may be limitations on some types of instruments and techniques (e.g. non-ATEX)
- Guidance documents could be an alternative route or precursor to full standards, to issue much needed guidance quickly and urgently. The precursor route could involve developing guidance, working with early adopters and site operators to develop a useful interim guidance document until a standard is available. The guidance document could be trailed at operating sites. Need to consider who would be best to lead this work: regulators or industry? Guidance documents would be easier to update than standards.
- Any standards and guidance should be based on NG or methane sectors to encourage adoption.
- Consider developing 'best practice guides' which could be developed at a top level to cover the general steps and mirror best practice for NG and methane. The validated methods being developed by NHyRA could be used as a basis best practice guide. Also, the report that describe the measurement campaigns being undertaken by NPL for DESNZ could also be used to develop best practice guides, the report is still in process of being published. It would be of value to refer to these documents when published, could be used to refer operators to.
- The challenges are being too specific what operators need to do, write a generic best practice guide or guidance document to begin with, then it should evolve as

experience grows, since currently industry have little experience and little evidence data.

- Would be useful to cover how to undertake a leak detection campaign (an example could be the report from the recent NPL / DESNZ project, has been shared with the EA, had yet to be published), current technologies available, how to test (monitor) different types of components, what organisations (the different stakeholders – who to approach) are around, and eventually awareness of what standards are available.
- There is a need to support industry (usually via best practice or guidance documents or metrology community for complex or novel scenarios), where to detect, how to test components, is a defined process or method needed, even difference between pumped v passive sniffers, time spent on (monitoring) components. What is covered by a (monitoring) specification, proficiency testing, what are operators obligations etc.
- American Society of Mechanical Engineering (ASME) have industrial design standards for hydrogen piping and pipelines [66]. These need to be reviewed for suitability.
- Pressure system directives provide regulations and tests for before the system is live and a code of practice for performing tests. There is DNV guidance [67] on repurposing for hydrogen use.
- There is fast shifting ground around policy, the Hydrogen Energy Association is interested in standards and anything to encourage industry to lead more would be beneficial. Industry has a variety of members; some are in the early stages of development and may not have thought this far ahead. There is a lack of standards for hydrogen monitoring. It is important to engage with industry to write best practice guides, guidance documents and standards that will be adopted. Action: To explore the possibility of a joint industry and regulator working group

Q2: What guidance do instrument suppliers need?

- Developers of instruments are aware of the top-level (monitoring) needs, but not necessarily about the details required for hydrogen monitoring. What details need to be identified? For example, to appreciate the challenges / differences between laboratory and field (at representative sites) monitoring.

- Do industry instrument suppliers need to be *told* what type of instruments (and performance) needs to be developed. An approach could be to set performance standards (based on data reporting needs) with the aim that new products can be developed to meet them. However, this could delay their adoption if performance targets are too stringent for the technology to meet them. A wider remit may be necessary, and the target revised based on outcomes. It is important to identify the gaps between the technology available / emerging technology and what is needed.
- There needs to be more opportunities to engage with instrument suppliers to help ensure that instruments are designed fit for purpose (including testing at representative sites). Need to consider instrument relevant specifications (e.g. uncertainty). Validation and testing should resemble conditions out in the field / real case scenarios.
- Consider using the Product Certification Scheme (CSA) [68]. Key components are that the scheme is based on recognised standards (e.g. ISO), incorporates testing and evaluation, factory inspection and auditing and ongoing surveillance. For some products (e.g. electrical appliances) it is mandatory whilst others are voluntary. Such as scheme could add value in terms of building industry confidence in using instruments.
- What information do instrument suppliers need? Intended applications, performance requirements, sight of what is coming next in terms of user industries and monitoring requirements (e.g. portable or fixed, frequency of monitoring or continuous), calibration requirements (e.g. how often).

Q3: What training and competencies are needed?

- May need stratified levels, for example, training and competence for : i) awareness and safety, ii) measuring methods and interpretation of data and iii) supervision.
- The MCERTS personnel competency scheme assesses the capabilities and skills of stack emissions monitoring staff. Operator's capabilities and skills are recertified every 5 years. The scheme syllabus is updated so that they are assessed on the latest standards.
- Smaller sites may want to have the capabilities to undertake monitoring surveys themselves. This could be considered using best practice guides.
- Need to work with UKAS to develop an accreditation scheme for organisations.

Q4: How will schemes scale up in the future?

- As mentioned earlier more evidence data is needed (so that decisions made about how monitoring is conducted can be defended). Even with the lack of data (currently) how can we use the available data to start paving the way to create predictive tools for when more sites are operating?
- More workshops with researchers, industry, regulators, etc. are needed to speed up the process to develop monitoring schemes, but what engagement / workshops are needed?
- Need for data logging systems on sites that can share data (reported data) to build up a knowledge base, such data may need to be anonymous as organisations want to avoid sharing commercially sensitive information. A solution could be to anonymise reported data e.g. “these specific valves start leaking after x years”. Need to consider commercially sensitive information, e.g. of site design.
- A potential issue is that CO sensors are sensitive to hydrogen too. This will be important to consider in terms of certain scenarios, for example: monitoring emissions from combustion.
- How do we scale it up? ...do we *need* to scale it up? What would scaling up look like? Is the landscape going to change significantly? The UK hydrogen strategy [69] sets out the UK’s ambitions, priorities and roadmap for hydrogen in the 2020s, including the scaling up of hydrogen production. There was a view during the workshop that *flexibility* is an important consideration in “scaling up”, for example in the development of best practice guides to ensure that they are fit for purpose to a wide range of scenarios and shifting landscape.

Q5: What are the measurement needs from a metrology perspective?

- Measurement requirements depend on specific scenarios and scopes. Need to consider whether monitoring will be detection or quantification based.
- Basing monitoring on concentration thresholds not compatible with all techniques, mass or volumetric based threshold may be more appropriate.

- Need to also consider appropriate calibration, traceability and reference materials for different techniques.
- There needs to be more research in dispersion properties of hydrogen, to understand the feasibility and scope of technique that measure over large areas up to site level, for example tracer correlation and techniques that measure remotely from the source.
- There needs to be research into underground leaks in soil behave and can be monitored.
- One possible path to standards is to define emissions values on GHG effects, compare hydrogen indirect GHG effects to methane, but there may be some caveats since there are many more aspects impacting the potential values of the emission levels.

Other points:

- Engagement with Health and Safety Executive (HSE): Safety is covered elsewhere (existing guidance and standards) but where unsafe leaks occur they would still need to be reported, if there's an incident/event where hydrogen is released. Different threshold for environmental reporting to that of reporting to HSE. HSE interested in reducing any emissions since any leak could develop into a larger issue. LDAR program could be used to mitigate this circumstance, to demonstrate operator is keeping ahead. However, HSE is not interested in quantification.
- Can odorised hydrogen be used a tracer? – need to consider a potentially different leak behaviour. Could a system be shut down and then drained, then pressurised with a proxy gas to find leaks. This approach could be considered for systems like boilers to test integrity. What actions are needed if a leak is detected?

  ISO/TC 197 [70] is the international organisation for standardisation technical committee responsible for the standardisation of systems and devices used throughout the hydrogen value chain (production to end use), this includes infrastructure standardisation, safety and performance standards.

  Examples of existing standards that cover the integrity of in structure include:

ASME B31.12 [66] covers hydrogen piping and pipelines; ASME Boiler & Pressure Vessel Code (BPVC) for Pressure vessels and storage systems [71] and ISO 19880 1:2020 for hydrogen refuelling stations [72].

- Adding tracers (CO_2, dyes) depends on application—some industrial hydrogen applications need purity.

Annex 3: List of abbreviations

Table 7. List of abbreviations

Abbreviation	Definition
AE	Alkaline Electrolysers
AEM	Anion Exchange Membrane
AMS	Automated Measurement Systems
ATEX	EU safety directives for explosive atmospheres
ATR	Auto Thermal Reforming
BAT	Best Available Technique
BSI	British Standards Institution
CCUS	Carbon Capture Utilisation and Storage
CEMS	Continuous Emission Monitoring System
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CSA	Chief Scientist's Group
DESNZ	Department of Energy Security and Net Zero
DIAL	Differential Absorption Lidar
DSIT	Department for Science, Innovation & Technology
EPA	US Environmental Protection Agency
FBG	Fibre Bragg Grating
FEDS	NPL's Fugitive Emissions Detection System

FID	Flame Ionisation Detector
GHG	GreenHouse Gas
GWP	Global Warming Potential
HAR	Hydrogen Allocation Round
HEMS	Handheld Emissions Monitoring Systems
HSE	Health and Safety Executive
H_2	Hydrogen
IR	Infra-red
LDAR	Leak Detection And Repair
LEL	Lower Explosive Limit
LOD	Limit of Detection
MCERTS	Environment Agency's Monitoring Certification Scheme
MEMS	Micro Electro Mechanical System
MOS	Metal Oxide Semiconductor
MJ	Mega Joules
Mt	Mega tonne
MW	Mega Watt
NG	National Gas
NHyRA	pre-Normative Hydrogen Release Assessment
NMVOC	Non-Methane Volatile Organic Compound
NPL	National Physical Laboratory

OGI	Optical Gas Imaging
•OH	Hydroxyl radical
OPTHYCS	Optic Fibre-based Hydrogen Control Systems
PEM	Proton Exchange Membrane
Pd	Palladium
ppm	parts per million
PT	Performance Test
RDM	Reverse Dispersion Modelling
RNG	Reverse Dispersion Modelling
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolysers
SPR	Surface Plasma Resonance
TC	Tracer Correlation
TRL	Technology Readiness Level
VOC	Volatile Organic Compound

Annex 4: Glossary

Table 8. Glossary

Abbreviation	Definition
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) needs to be defined. An example of a continuous emission is a landfill. The emission rate may vary.
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.
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.
Monitoring	A generic term used to describe measurement, location and/or detection of emissions
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.
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-sensor (Sampling strategy)	A point-sensor must be deployed in the measurement area and typically provides a much smaller coverage area
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), which needs to be physically located within the plume, or within the target region.

Sampling strategy	Describes how the measurement is collected and represented, and the platform used.
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).
Technique	A generic term used to describe a type of measurement instrument, sampling strategy, emissions quantification, or data process.

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Hydrogen monitoring and measurement: Evidence report to support the development of LDAR and MCERTS standards

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