PRE-NORMATIVE RESEARCH ON HYDROGEN RELEASES ASSESSMENT

D2.1

Determination of possible hydrogen detection and measurement techniques and methods

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EXECUTIVE SUMMARY

Hydrogen (H_2) will play a pivotal role in achieving climate neutrality through its use as an alternative energy conveyor through which alternative and green energy sources can be widely used, both at industrial and domestic levels. The leakage of hydrogen into the atmosphere is a concern as it can indirectly affect the lifetime of methane in the atmosphere and prolong its greenhouse effect. Minimising leaks is also important for safety and optimising the efficiency throughout the hydrogen value chain. The pre-Normative Research on Hydrogen Releases Assessment (NHyRA) project aims to fulfil the knowledge gaps about the amount of anthropogenic H_2 released into the atmosphere from the entire H_2 value chain.

The work in this report identifies hydrogen detection and measurement methods, techniques and instruments, covering commercially available and emerging (near-to-market and future). This report will provide input to work package 2 (development of hydrogen monitoring methods) and WP3 (testing and validation of methods).

There are no established methods for monitoring hydrogen emissions emanating from fugitive and vented emissions other than systems used to detect hydrogen emissions for safety purposes. Therefore, methods are needed to detect and quantify emissions over a wide range of concentrations and spatial and temporal scales. Many instruments available on the market can measure hydrogen concentration, and their suitability to detect and/or quantify emissions sources will need to be assessed. Such techniques include sniffers, passive instruments, acoustic cameras, and OGI (Optical Gas Imaging) combined with a tracer.

Techniques for monitoring hydrogen emissions have been categorised as follows:

- Detection of leaks at component level. Sniffers, passive sensors, and acoustic cameras are candidate techniques to consider when developing methods.
- Detection and quantification of leaks at component level. High-flow sampling is a candidate technique to consider for method development.
- Surveillance and/or quantification of emissions at area/site level. Distributed networks and tracers are candidate techniques to consider for method development.

Important factors to consider during the selection of instruments and sensors, development, test and validation of methods are: the gas composition of emission sources (for example, what effect does water vapour have on the measurement), what is the threshold for a leak?, effect of odorants on the monitoring method, review the type of emissions that are in scope which may depend on the instrument design and capabilities (for example, is it feasible with the scope of the project to develop a method for measuring pure hydrogen from a vent?), to identify the level of performance required for instruments to fulfil the requirements of testing and validation in work package 3.

1. INTRODUCTION

Hydrogen (H_2) will play a pivotal role in achieving climate neutrality through its use as an alternative energy conveyor through which alternative and green energy sources can be widely used, both at industrial and domestic levels. The leakage of hydrogen into the atmosphere is a concern as it can indirectly affect the lifetime of methane in the atmosphere and prolong its greenhouse effect [1]. Therefore, mitigating hydrogen emissions is important. In addition, Hydrogen gas has a wide range of flammable concentrations in air and may ignite more easily than natural gas. In addition, some metals and alloys can become brittle when exposed to hydrogen gas, particularly in high-pressure environments [2]; this further increases the risk of significant leaks occurring. There is an additional economic purpose for minimising hydrogen leaks, as it is a valuable commodity.

As larger amounts of hydrogen are expected to be produced in the future, assessing the quantity released from the H_2 chain is challenging since insufficient or no standardised data can be found in the literature. The pre-Normative Research on Hydrogen Releases Assessment (NHyRA) project aims to fulfil the knowledge gaps about the amount of anthropogenic H_2 released into the atmosphere from the entire H_2 value chain.

To achieve its aim, NHyRA will develop the following mitigation strategies:

- Create a universally accepted and open-access inventory of the H2 releases to serve as a reference for the scientific and industrial community.
- Deliver validated methodologies and techniques for measuring or calculating these releases.
- Improve the quantification capability of small and large releases.
- Identifying and prioritising effective mitigation actions.

Work package 2 aims to develop measurement-based methods for detecting and quantifying hydrogen emissions. This report is the deliverable under the first activity (Task 2.1) which will identify hydrogen detection and measurement methods, techniques and instruments, covering those that are commercially available and those that are emerging (near-to-market and future-looking).

This report will:

- Identify the relevant characteristics and properties of emission sources that could help select, test and validate monitoring methods.
- Define what a monitoring method should consist of and define the data quality metrics of the data reporting requirements (what data is required) and data measurement requirements (how it is obtained),
- Summarise existing and emerging techniques and their advantages and disadvantages,
- Define relevant instrument properties and characteristics and reference a spreadsheet that provides a review of commercial off-the-shelf instruments.

The inclusion of manufacturers in this report does not represent an endorsement. The manufacturers and products identified in this report are not a complete list, they represent examples available at the time of writing. Other instruments may be available.

Work package	Description	WP Leader	Timeline (months)
WP1	H2 releases inventory	UNIBO	1-36
WP2	Methodology development for H2 releases' quantification	INIG	3-27
WP3	Methodology validation and field tests assessment	NPL	7-34
WP4	H2 releases from supply chains	ENGIE	12-34
WP5	Hydrogen release scenarios	FBK	12-36
WP6	Dissemination, communication & exploitation	GERG	1-36
WP7	Coordination and Project Management	SNAM	1-36

2. EMISSIONS SOURCES

Work package 1 defines the hydrogen release inventory. This section aims to define the relevant emission source parameters needed to identify and select hydrogen monitoring sensors and instruments and to develop, test and validate the monitoring methods throughout work packages 2 and 3.

Emissions sources (in general) are typically grouped into the following categories, as defined in work package 1.2:

- Fugitive emissions:
  These are unintentional emissions, which may be due to:
  - Leaks due to connections/loss of tightness from components such as pipework and flanges.
  - Permeation.
  - Emissions from gas sampling operations or gas analysis equipment.

- Vented emissions:
  These are emissions from intentional activities:
  - Operations, such as: purging and venting, regular emissions of devices, starts and stops and boil off (evaporation).
  - Incidents.

- Incomplete Combustion: Unburnt hydrogen in exhaust gases from combustion gases.
  This type of emission may impose additional challenges such as physical (e.g. height of flares, temperature), or the composition of the exhaust (e.g. water vapour).

All these emissions may diffuse over a large area, for example, from multiple small vents.

Emissions from maintenance operations (such as purging) could result in high mass emission rates released over a short period of time. Monitoring such emissions may require instruments and their associated sensors to operate and measure up to pure concentrations of hydrogen.

Engineering calculations may be a more appropriate method for large vents to estimate emission rates rather than monitoring. Even if this is not in scope, however, types of engineering calculations are listed in the annex for completeness.

It is important to define and describe the properties and characteristics of these emissions sources (as much as practically possible), which would help identify the most appropriate and cost-effective monitoring technique. The following examples have been obtained from a methane taxonomy [3] used to describe emission sources; many of these are relevant to hydrogen, and this list is not exhaustive:

- The source's physical properties, such as its size and height, could influence the choice of monitoring technique (e.g., monitoring directly of small components or monitoring over a large spatial area). Source height could determine accessibility for monitoring.
- The properties of the emissions plume:

- Temporal characteristics: continuous or non-continuous.
- Gas composition: list of species (e.g. pure hydrogen or blends, water vapour).
- Range of concentration or leak rates.
- Source type: diffuse, fugitive, point or elevated.

- Local environment such as topology (this could affect techniques that depend on wind measurement, for example), sources of interference (i.e. other gases being emitted that could interfere with the measurements).
- Relevant maintenance activities, e.g. planned venting resulting in high concentrations.

It will be important to track and record operational parameters during emissions monitoring, and such tracking will help characterise intermittent emissions sources.

3. HYDROGEN MONITORING

3.1 Background

There are sensors available for monitoring hydrogen releases for safety purposes, and there are standards in place for their testing and use [4][5][6][7][8]. However, there is a lack of guidance on monitoring for leak detection and quantification (determination of mass emission rates) for emissions on all types of releases even if they don't pose a safety risk, i.e. leaks that generate lower concentrations than the Lower Explosive Limit (LEL). The purpose of monitoring emissions is as follows:

- To provide evidence data for regulatory compliance, for example, by undertaking a series of targeted measurements and then combining those measurements into a site total.
- To identify and locate emissions such that mitigation strategies (for example, repairs) can be implemented to reduce emissions, thus minimising the impact on the environment, improving safety and minimising the loss of a valuable commodity.
- To validate emission estimates derived from engineering calculations.
- To define emission factors from activity data and measurements.
- To carry out (research) exploratory monitoring to better understand the characteristics of emissions and help define data reporting requirements; also help develop and test monitoring methods in realistic conditions.

Currently, there are no established methods for monitoring hydrogen emissions into the atmosphere; however, there are:

- Instruments available on the market that can detect and measure hydrogen concentration.
- Established methods and techniques to measure other pollutants (such as methane) that could be considered and repurposed for monitoring hydrogen.
- Emerging (near-to-market or future-facing) instruments and techniques.

3.2 The constituents of a monitoring method

As well as an instrument, a monitoring method must define the measurement requirements:

- Scope. A clear definition of the physical magnitude to be measured: gas concentration or leak rates, whether they are direct measurements or estimations (for example, based on models), and if applicable a means for converting gas concentrations to emission rates.
- A sampling strategy that describes how the measurement is performed and how the data are collected, assimilated, and reported.
- Measurement objectives and an agreed and established measurement procedure.

- Metrology factors (evidence of validation, traceability, calibration, applicable standards, auditing, and ways to validate method performance and method transparency) and a quality system to provide confidence in data.
- Training and competencies required.
- Limitations, dependencies and assumptions.
- Recommended instruments and techniques.

The choice of monitoring method (and its associated instruments) should be based on the data reporting requirements (refer to Table 1), the type (e.g. fugitive, vent, etc) and any known characteristics of the emissions source. The data reporting requirements define *what* needs to be measured. The measurement requirements (defined in the method) describe *how* the measurements will be undertaken.

It is recognised that the choice of method and instruments may be limited by the cost and availability of methodology and instrumentation. Understanding the technological and methodological gaps between what is available and what is needed is important, as this should help drive innovation.

Table 1: data reporting requirements

Properties		**Suggested definition**
Spatial / Temporal	Spatial coverage	Refer to Figure 1 below
	Spatial resolution	The smallest change in a measured quantity that causes a perceptible change in measured value [9].
	Temporal resolution	
Measurand	Uncertainty	Value as a percentage of the mean. Specify whether it is standard or expanded.
	Coverage factor	Interval containing the set of true quantity values of a measurand within a stated probability.
	Detection limit	The lowest signal that can be reliably detected with a sufficient degree of confidence. Also referred to as the limit of detection. The analytical or technological detection limit may differ from the method detection limit.
	Quantification limit	Minimum quantifiable emissions, based on the uncertainty of the method
	Measurement range	Range of measurements to be covered by the method, lowest (for example, sensitivity) to highest value (for example, highest emission rate likely to be observed).

	Species covered	Species to be covered by the method
	Class	Detection, Quantification, Estimation and/or Localisation to be covered by the method
	Type and units	Type of output to be covered by the method, i.e. emission rate, concentration, threshold or complex (described in the descriptions below)

3.3 Monitoring categories

Measurements and data reporting must cover a wide spatial range (from individual components to site level) and temporal range (snapshot in time to continuous monitoring). Figure 1 illustrates the different temporal and spatial measurement scales involved in covering a site; similar maps are used to describe the methane monitoring space [10]. The x-axis represents the temporal scale from a continuous measurement to a 'snapshot'. Periodic could mean regular snapshots or a near continuous measurement but with gaps in coverage. The y-axis represents spatial scale: i.e. component (for example, a flange); functional element (for example, a storage tank); site and multiple sites clustered together.

It is proposed that monitoring techniques for the monitoring of fugitive and diffuse (from vented emissions or sources of combustion) emissions are categorized as follows:

- Detection of leaks at component level.
- Detection and quantification of leaks at component level.
- Surveillance and/or quantification of emissions at area and site level.

The spatiotemporal area covered by the first two categories listed above is shown in the lower portion of Figure 1. Techniques within these categories detect and/or measure emissions sources at the component level, typically as a "snapshot" or over periodic time intervals, for example, before and after a repair.

The spatiotemporal area covered by the "area and site level" category is shown in the upper portion of Figure 1. Techniques within this category detect and/or measure emissions over a wide area (for example, diffuse emission from multiple sources), from functional elements to site level.

It is conceivable that the scope of leak detection and quantification techniques could be extended to include monitoring of direct emissions from point sources and scenarios where there could be high concentrations of hydrogen (purging) – this will depend on the choice of sensor, instrument design and how it is deployed.

It is envisaged that the map shown in Figure 1 could be used to help match the capabilities of the monitoring technique/ method against the data reporting requirements. The data reporting requirements will be dependent on the purpose of the monitoring; for example, the purposes were defined above in section 3.1. For example, if the purpose of the monitoring is to provide evidence data for regulatory compliance, then the data reporting requirement could be for a total emissions rate (with an uncertainty) for the site to be reported annually. If a leak detection and quantification method is to be used, then the reported total will likely consist of the assimilation of many snapshot measurements.

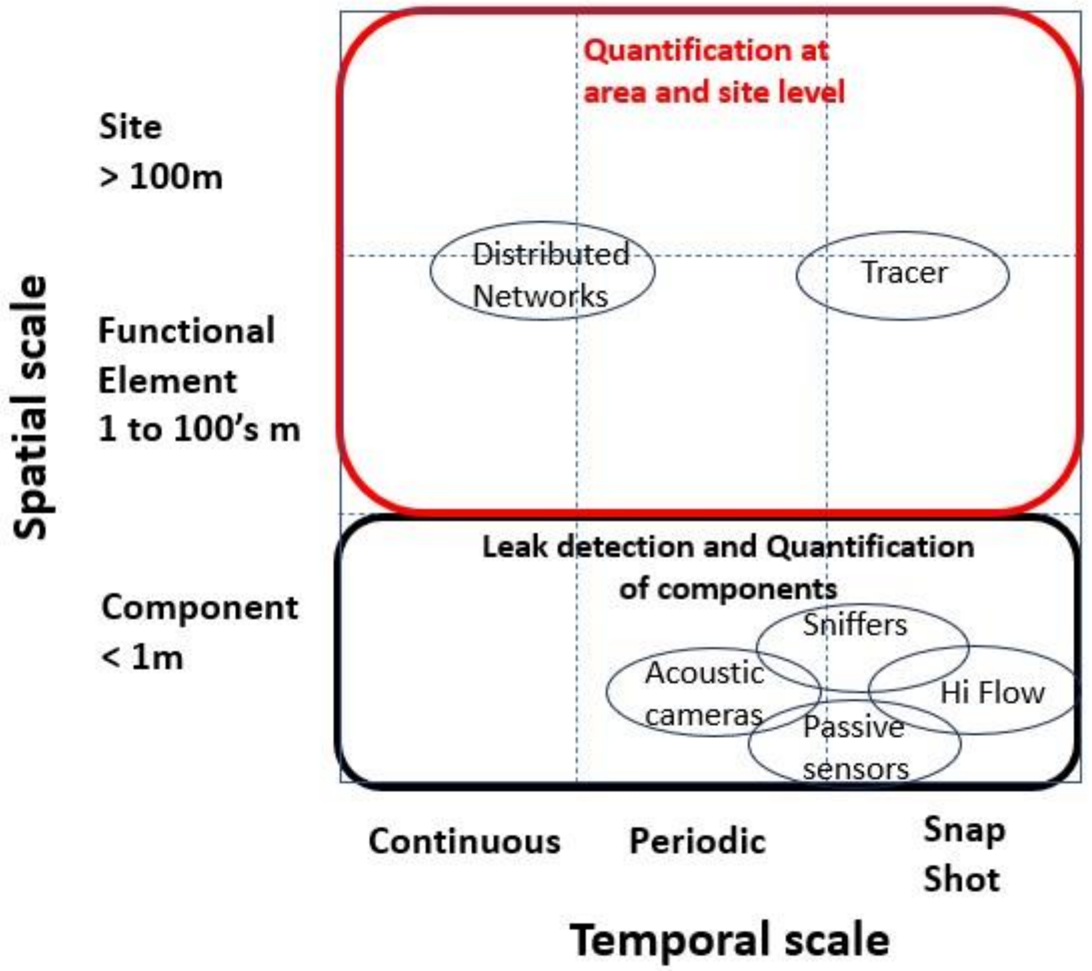

Figure 1. Hydrogen monitoring temporal and spatial scales.

Another important distinction is made between point sensing and remote sensing techniques (refer to the definitions in the Appendix). Remote sensing techniques can potentially monitor areas that are difficult to physically access, including hazardous areas (for example, flares), and monitor larger spatial areas more efficiently than point sensing techniques.

3.4 Instrument characteristics

Table 2 lists instrument properties and characteristics to consider. The data source must be noted, for example: the manufacturer datasheet, testing carried out or an opinion. It is envisaged that some manufacturers' data or opinions will need to be verified by independent testing, in particular:

- Sensitivity, linearity and range.
- Selectivity to hydrogen, in particular for methane and water vapour.
- Short-term and long-term drift.

Table 2: Instrument properties and characteristics

Properties		Suggested definition
Spatial / Temporal	Spatial range (m)	(Remote sensing, open path techniques only).
	Spatial resolution (m)	(Remote sensing, open path techniques only). The smallest change in a measured quantity that causes a perceptible change in measured value [9].
	Response time (s)	This requires a standard definition.
	Time to provide a measurement (s)	Time between sampling an aliquot of gas and a reading presented to the user. This may include time to take multiple readings and calculate an average.
Measurand (gas concentration)	Intended gas species	e.g. hydrogen, methane etc
	Sensitivity	The ratio of the change in the measured value to the corresponding change in the value of the measured quantity [9].
	Maximum concentration	As stated by the manufacturer, but this may need to be verified by testing.
	Precision	Closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions [9]

	Short and long-term drift	Short (seconds) and long term (hours to days), time periods and units to be defined.
	Accuracy	Closeness of agreement between a measured quantity value and a true quantity value of a measurand [9]. Accuracy is a qualitative statement.
	Measurement range	Range of measurements to be covered by the method, lowest (for example, sensitivity) to highest value (for example, highest emission rate likely to be observed).
	Displayed units	e.g. ppm, %LEL, %vol
Sample inlet (sniffer only)	Inlet pressure	
	Sample flow rate	
Physical	Size (width, length ,height) cm	To provide an indication of portability
	Weight (kg)	
	Power source	e.g. battery to 230Vac
	IP rating	e.g. IP67
	Explosion proof class	e.g. IECEx and ATEX
	Operating temp. range	
	Operating humidity range	
Weblink to datasheet		
Descriptive	Principle of operation and technology	Refer to the sensor type below (e.g. catalytic)
	Intended or potential application	e.g. leak detection, quantification or site quantification
	Physical dependencies	e.g. Indoor or sheltered use, requires oxygen in the sampled air
	Data dependencies	
	Price	Euros
	Training required	Autonomous <-> expert
	Calibration process and period	
	Maintenance management	
	Quality process	
	Advantages	
	Disadvantages	
	Technology Readiness Level (TRL) [11]	
	Notes	

3.5 Detection of leaks at the component level

The division of hydrogen leak detection techniques is shown in Figure 2. Computational techniques (shown on the right-hand side) are at a low stage of development (TRL) for leak detection. Therefore, these techniques are out of scope of the analysis included in deliverable D2.1, while they will be analysed in more details in other project's tasks (Task 2.3 and 2.4) and deliverables. However, the most known computational techniques are summarized in Annex 2 for completeness. Sub-categories of techniques described in this section are: sniffers and passive sensors, acoustic cameras and optical gas imaging. A wide range of instruments are available that utilise these types of sensors (possibly regarded as up to TRL 9 in some applications). However, for the scope of this work (for leak detection at the component level), these techniques will need to be validated (work package 3) to be considered TRL 9.

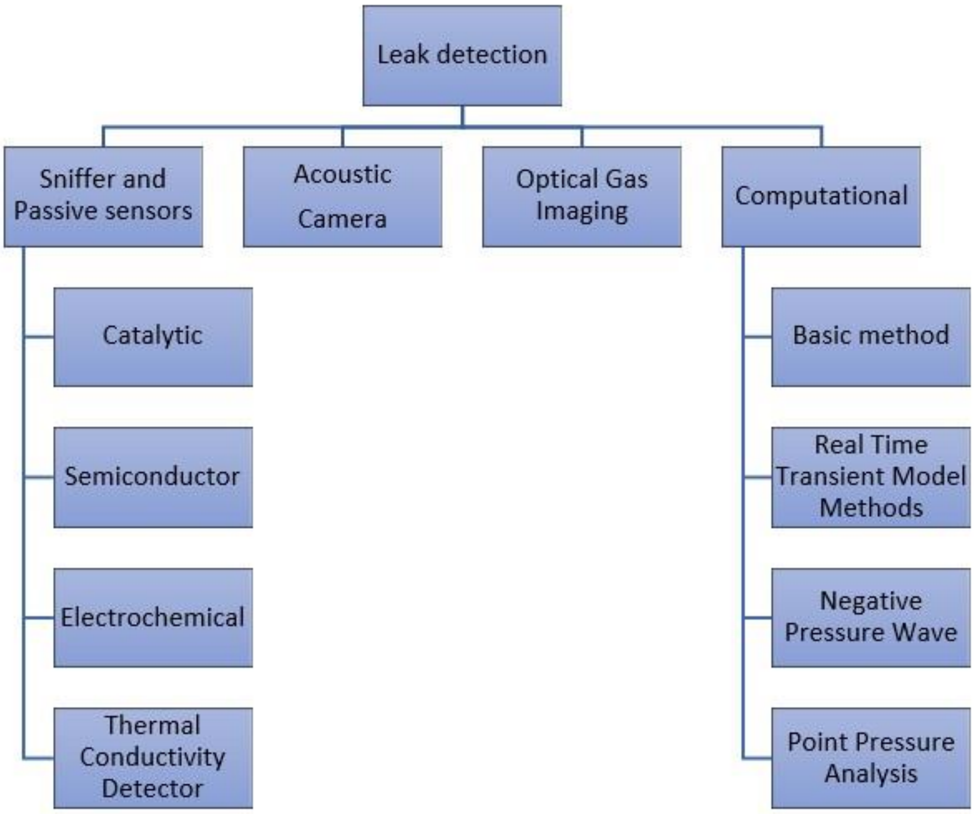

Figure 2. Hydrogen Leak detection methods/ techniques

3.5.1 Sniffers and passive sensors

This sub-category of technique typically uses battery-operated and handheld portable instruments that measure gas concentration. These instruments must be in situ (within the emissions plume). Therefore, they will be unsuitable for monitoring inaccessible areas and may (according to their design) be unsuitable for monitoring hazardous areas. Sniffers are instruments where a sample of gas to be measured is directed towards a sensor by means of a generated air flow. Passive are instruments where the sensor is placed within the gas being measured without any generated air flow. The qualitative and quantitative measurement performance of sniffers and passive instruments depends on the type of sensor used, the instrument's design and the data processing used to convert the sensor output to an output. Furthermore, the emission plumes usually have complex geometries and could vary over time (mainly due to local wind); for that reason, the measured concentration value would depend on the distance at which the detector tip is located and on the sampling rate of the internal pump. Typical sensors used to detect hydrogen are:

- Catalytic combustion sensors.
- Electrochemical sensors.
- Metal-Oxide-Semiconductor (MOS) sensors.
- Palladium-Alloy sensors.
- Thermal Conductivity sensors (TCD).

A summary of the operation of catalytic, electrochemical, semiconductor sensors and thermal conductivity detectors is provided in [12] to [16].

The basic advantages and disadvantages of individual types of sensors are presented in Table 3. The comments made in this table are either based on the manufacturer’s data or commonly held assumptions. Some advantages and disadvantages listed may need to be verified by experiment as the sensor's performance may depend on intended use and conditions. For example, catalytic sensors are regarded (in this table) as having a linear characteristic. However, this needs to be verified over the concentration range in which the sensor will be used.

Table 3, Advantages and Disadvantages of sensor technologies.

Advantages	Disadvantages	References
	Catalytic combustion sensors	
• Has a linear characteristic. • Resistant to interference effects (temperature and humidity) • Easy to install and calibrate, however, it requires regular calibration. • Long lifespan (6-8 years) if the catalyst does not become poisoned. • Low cost.	• The catalytic surface can be deactivated by contaminants such as sulphur compounds. • Prolonged exposure to high concentrations of explosive gas reduces the sensor's lifespan.	[12], [13]

• Ability to detect various gases, including hydrogen.	• Not resistant to external factors such as poisons (such as sulphurated compounds). • Poor selectivity to hydrogen (i.e. ability to discriminate hydrogen from other gases). • Require Oxygen for combustion (maybe un-suitable for vented gases)	
Electrochemical sensors		
• High sensitivity and measurement accuracy • High selectivity (dependent on the filter system) • Long lifespan of 2-5 years. • Low power requirements, low energy consumption. • Ability to detect a wide range of gases. • Operation at ambient temperature. • No influence of humidity on sensor operation.	• Relatively long response time up to 2 minutes, compared to less than typically 30 seconds for other types of sensors. • Susceptible to blockage by dirt and other contaminants. • Limited sensitivity to low molecular weight gases, depending on the design of the membrane. • Require recalibration and periodic maintenance.	[12], [13], [14]
Metal Oxide Semiconductor sensors		
• High concentration of the measured gas does not poison the sensor. • Ability to operate in a wide range of atmospheric conditions. • Long lifespan of 2-10 years depending on environment. • Lightweight and mechanically durable.	• May exhibit interference effects from various gases. • Has a high power demand due to the high operating temperature. • Sulphur compounds and weak acids may contribute to sensor poisoning. • Even small continuous amounts of the measured gas cause the sensor to gradually saturate.	[12], [13],
Palladium Alloy Sensors		
• Selectivity to hydrogen. • Fast response time. • Small physical size.	• Sensitive to changes in water vapour concentration (humidity). • Non-linear. • Not suitable for very high concentration of hydrogen (caused blistering). • Sensitive to Sulphur contaminants. • The sensors by themselves are difficult to source commercially.	
Thermal Conductivity Detectors (TCD)		

• Fast response time. • Universal, it can analyse all possible gaseous species.	• High detection limit: in the order of 1% H_2 for some commercial sniffers. • Non selectivity.	[15]

An example of a passive instrument is an Infricon Sentrac Strix, designed to measure hydrogen concentration. It uses a Palladium-alloy Field-Effect Transistor-type (FET) gas sensor mounted on the end of a probe. Another example is a Teledyne GS-700 (H_2) sniffer instrument designed to measure hydrogen and natural gas (or methane gas) concentrations. This instrument uses a catalytic and thermal conductivity type sensor for hydrogen and an infrared sensor for methane.

3.5.2 Acoustic cameras

These types of instruments are typically battery-operated handheld portable systems that detect the acoustic waves produced by the turbulence generated by a gas leak.

An acoustic camera is an ultrasonic imaging instrument for locating and characterizing sound sources, producing a graphic-style sound display. The acoustic properties of a leak will depend on the physical size and geometry of the hole through which the gas is emanating, the ratio of pressure (inside the containment vessel and external atmosphere) and material properties.

Acoustic cameras could be considered *remote sensing techniques,* which do not necessarily need to be physically located within the emissions plume (or even in the region where emissions may occur). Typically, the detection can be done from some meters to several tens of meters, depending on the size of the leak/emission. Acoustic cameras could conceivably be used to complement other techniques, for example, a camera used to detect the presence of leaks and then an appropriately designed technique used to quantify the leak.

An example of an acoustic camera is a Distran Ultra Pro X hand-held ultrasound imaging camera capable of accurately locating gas leaks from several meters such instruments could be useful for screening purposes (i.e. detecting and localising leaks). Another example is a FLIR Si124-LD Plus system. Both instruments contain 124 microphones that detect ultrasonic noise generated when gas escapes through a leak.

3.5.2 Optical Gas Imaging (OGI)

Optical Gas Imaging (OGI) is a technique based on thermal (infrared) imaging technology. By adding a spectral filter, a thermal imaging camera can be made to be specifically sensitive to infrared active gases. In the case of methane, cameras may operate at 3.3 µm or 7.5 µm wavelength. 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. Although the technology has been around for several decades, in the last 10 years, OGI has been commonly used for leak detection in natural gas processes. Cameras can be used for detection of larger emissions at significant distances but are most commonly used for finding smaller component scale leaks at <3 metres from the equipment being monitored. An example of a handheld variant of an OGI is shown in Figure 3.

Hydrogen, unlike methane, has limited absorption in the infrared region. Therefore, the OGI technique cannot directly detect hydrogen leaks. Great 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. Tests have been carried out using sulphur hexafluoride (SF_6) as a tracer. SF_6 is a gas that absorbs infrared radiation well; therefore, it seems an ideal tracer for OGI techniques. However, due to its high Global Warming Potential (GWP_{100} of 23,500 or more) [17], other tracers were searched in parallel [18]. Currently, carbon dioxide is a tracer added to hydrogen that enables the OGI technique to detect leaks in the hydrogen value chain [18, 19, 20]. The research has shown that adding carbon dioxide to hydrogen below 5% allows for effective optical imaging of gas leaks from the hydrogen value chain. However, adding carbon dioxide will not be desirable for particular end-uses where hydrogen purity is important (for example, fuel cells).

Further studies could investigate whether impurities (already present) in the supply chain could be used as a tracer or whether the thermal or optical (e.g. refractive index) effects due to a leak could be exploited and detected using an OGI camera or other imaging technique.

Figure 3. An example of an uncooled and handheld variant of a gas imaging camera.

3.5.2 Choice of technique for method development

Sniffers, passive sensors and acoustic cameras currently offer the most potential in terms of providing, leak detection methods that could be developed and validated within this project's scope due to the technology's readiness and suitability for hydrogen. Further studies would be required to investigate OGI's suitability, which may be out of scope for this project.

3.6 Detection and quantification of leaks at the component level

For other gases and pollutants (other than hydrogen), these techniques may be regarded as up to TRL 9. However, for the scope of this work (for leak detection at the component level), these techniques will need to be validated (Work Package 3) to be considered TRL 9.

3.6.1 Indirect: e.g. concentration with correlation curves

The standard EN15446 [21] describes a method for estimating fugitive and diffuse emissions of VOCs of concern to industry sectors. The first step is to screen an area to detect and measure the concentration (in ppm). The second step is to determine the mass emissions rate of the leak by converting the concentration measurement into a leak rate using a response factor and then applying a correction factor. These 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 US EPA, or for high concentrations (above 100,000 ppm), an emission factor is used [22]. 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. In the case of hydrogen, it will be necessary to specify, test and validate a sampling method to capture a representative gas aliquot (a portion of the leaked gas blended with an unknown amount of atmospheric air) whose concentration can be correlated with emission rate.

3.6.2 Direct: concentration with sampling flow rate measurement

Such a technique could be based on a Hi Flow sampler [23] for quantifying natural gas, which has been successfully used for leak rate quantification in the natural gas industry for many years. Leaking components are loosely enclosed using a dedicated adaptor, and a measured flow of ambient air is drawn past the leaking component into the sampler. The resulting concentration is then measured by an instrument. A mass emission can be calculated using the measured concentration and sampling flow rate. A High Flow Sampler is illustrated in Figure 4. Such a technique could conceivably be adapted to quantify hydrogen leaks.

Figure 4. Example of a sampling method: Bacharach Hi Flow® sampler in operation.

3.6.3 Bagging or accumulation method

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 [22]. 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 an aliquot of air using a container constructed from inert material and then evacuating the undiluted leak from the container at a constant measured flow rate. This sample is then analysed in a laboratory. Also, this technique can be applied in the field using a sniffer detector (also called a leak detector), and some applications include using a reference leak EN ISO 20485:2018 [24]. 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.

3.6.4 Continuous Emission Monitoring Systems (CEMS) – to monitor direct emissions from vents and stacks

Continuous Emission Monitoring Systems, whose spatiotemporal coverage area is at the bottom left of Figure 1, are used for directly monitoring known emissions (pollutants) sources such as stacks and vents. These can be extractive (where an aliquot sample is delivered to an analyser) or in-situ. For the monitoring of direct emissions (for example, vents and stacks), the existing monitoring structure using CEMS based on many standards, such as EN14181 [25] and EN15267 [26], could be extended to include hydrogen. This would require defining emission limit values and performance requirements for the hydrogen CEMS. Developing a reference method for the CEMS certification field trials and calibrating

CEMS under EN 14181 would be necessary. Tests devoted to analysing potential interferences, selectivity to hydrogen, and method validations must also be performed to assess the method's performance, capabilities, and limitations. There are few instruments that, in principle, are currently available to continuously monitor hydrogen in stacks.

3.6.5 Acoustic Imaging

Most acoustic cameras allow you to determine the gas flow rate on the sound source's loudness. Measurement of gas emissions in l/min takes place in real-time. The accuracy of measurements and the limits of quantification are greatly influenced by ambient noise and other factors, such as the physical characteristics of the orifice from which the leak is emanating, such as its geometry and materials. Therefore, developing acoustic imaging to quantify emissions would be very challenging. Also, acoustic methods should not be used for those elements of the hydrogen value chain that are accompanied by noise, e.g. compressed hydrogen refueling stations.

3.6.6 Choice of technique for method development

Concentration with sampling flow rate measurement offers the most potential in providing a leak detection and quantification method that could be developed and validated within this project's scope since this technique has been widely used for methane.

3.7 Surveillance and/or quantification of emissions at area and site level.

This category describes techniques that estimate emissions across a more comprehensive spatial area, from functional elements to the whole site. Depending on the uncertainties of these methods, they may not be suitable for quantifying the emissions of a site. Still, they could be used to efficiently survey (to identify and localise emissions) areas to provide confidence that the leak detection and quantification methods employed have not missed any emissions sources.

3.7.1 Distributed networks – site level quantification

A distributed network comprises an array of sample inlets deployed around a site. Samples of ambient air are drawn from each tune inlet and, via tubing, are fed into the gas analyser capable of measuring the concentration of the target species. Figure 5 illustrates a distributed network. The analyser samples each tube inlet in turn, thus periodically sampling at each tube inlet location. Figure 6 shows a heat map representing the concentration measured at each sampling location. The concentration measurements are combined with reverse dispersion modelling of wind data to estimate emission rates.

NPL's Fugitive Emission Detection System (FEDS) [27] is an example of a distributed network. It has been deployed in operational field environments for methane detection and quantification and is currently at TRL 7 (system prototype demonstration in an operational environment). The analyser is an optical spectrometer that is tuned to measure methane. The system consists of up to 15 sampling independent sample inlets. Normally, the system is configured to sample at each tube inlet location over a period of approximately 4 minutes, cycling approximately once per hour. Using this configuration, the system provides periodic monitoring coverage at each location. The spatial coverage depends on the logistics of deploying tubing around the site and limiting the tube length (gas transit time between sampling inlet and analyser) to around 300m.

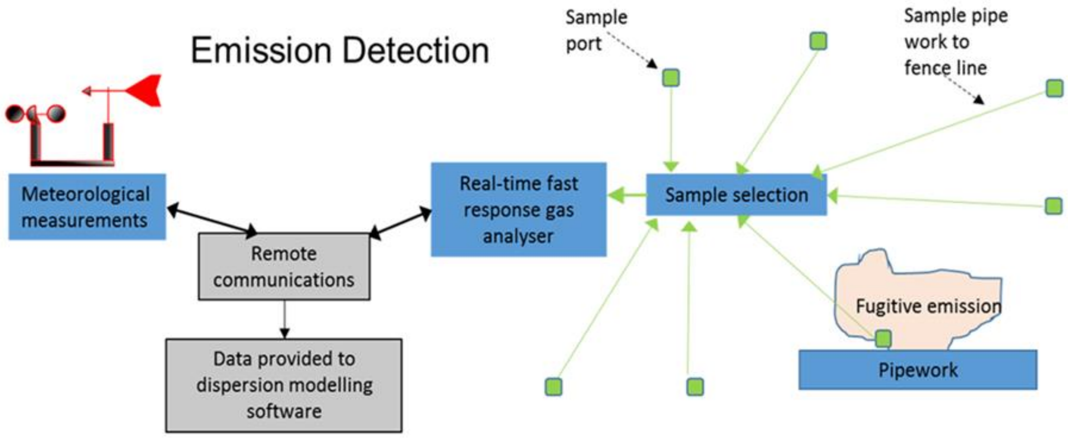

Figure 5. Sketch of a distributed network for gas emissions monitoring.

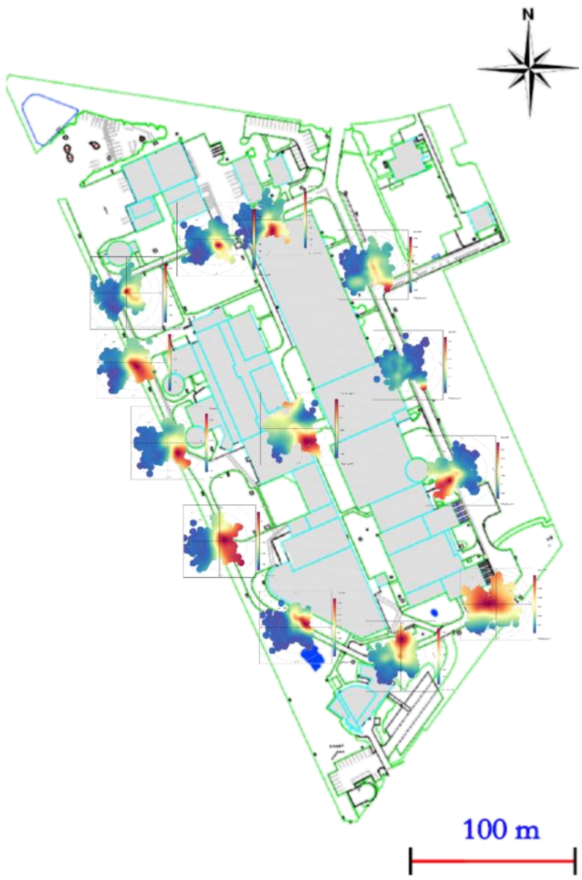

Figure 6. Concentration map calculated by FEDS.

NPL is developing a hydrogen version of the FEDS as part of the development of a continuous monitoring capability for hydrogen emissions; this will involve selecting a suitable analyser instrument, suitable tube material to transport hydrogen to the analyser, sampling period to ensure sufficient time period for gas transit time and purging of tune lines and reverse dispersion modelling applied to hydrogen gas. Future work (within the NHyRA project) is to develop the system to the same maturity (TRL) as the methane-capable system.

3.7.2 Tracer gas dispersion

Tracer gas dispersion is a remote sensing method used for quantifying fugitive emissions by relying on the controlled release of tracer gas at a known source, combined with concentration measurements of the tracer and target gas plumes [28]; work has been carried out to validate this method to quantify methane emissions from area sources [29].

A tracer gas is released at the known concentration, density and flow rate. Thus, its emission rate and its location are known. The tracer gas is chosen to have the same dispersion characteristics as the gas species of interest. The tracer gas and species of interest are measured downwind of the area of interest. Since the dispersion of the tracer and species of interest are assumed to be the same, then the concentration ratio between the measured species can be used to determine the emission rate of the species of interest.

This technique requires a fast response and high-precision analyser(s) to measure the concentration of the species of interest and tracer gases. Measurement should be made whilst driving at an appropriate distance downwind of the area of interest to map concentrations and identify the location of emissions. Figure 7 illustrates this technique.

This technique has been developed for methane, but for hydrogen, there needs to be further research, for example, to investigate the transport of hydrogen in the atmosphere and to determine the detection sensitivity for this approach.

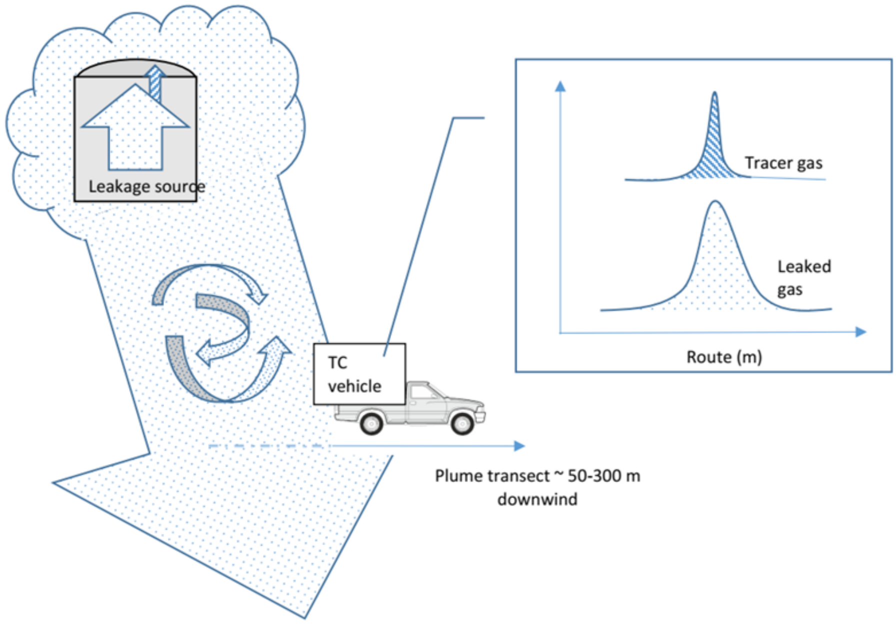

Figure 7. Illustration of the tracer technique

3.7.3 Choice of technique for method development

Both techniques mentioned above should be considered for further development since they are already widely used for measuring methane; development for hydrogen is considered feasible, although there are some further studies required and perhaps some challenges to be overcome, for example, developing reverse dispersion modelling techniques for hydrogen.

3.8 Quantification vent emissions

Estimation of hydrogen emissions during technological vents may involve direct measurements using instruments such as:

- Vane anemometer.
- Hotwire anemometer.
- Turbine meter.
- Electronic packing vent monitor.
- Calibrated vent bag.
- Coriolis meter.
- Orifice meter.
- Thermal mass meters.

However, direct measurement of emissions related to technological vents is challenging to perform for technological reasons, mainly resulting from the diversity of:

- Volume flow rate of the escaping gas.
- Duration of technological operation.
- Geometry of the measurement site.

For this reason, engineering calculations are often used when estimating emissions associated with process vents. These calculations require, at a minimum, measurement of:

- Gas pressure before and after surgery.
- Gas temperature.
- Ambient temperature.
- Gas composition (if it is not pure hydrogen).
- Physical volume of the vented equipment or system.

Table 4: Instrument properties and characteristics

measured parameter	device characteristics
gas pressure	measurement range covering the pressure change due to vent resolution max. 0.1bar accuracy +/-0.25% of full scale calibrated over the entire measurement range
gas temperature	measurement range covering the assumed range of gas temperature changes resolution max. 0.1C accuracy +/-0,15*0,002t calibrated over the entire measurement range

ambient temperature	measurement range covering the assumed range of ambient temperature changes resolution max. 0.5C accuracy +/-0,3*0,005t calibrated over the entire measurement range
gas composition	measurement range related to the qualitative and quantitative composition of the mixture hydrogen measurement uncertainty below 5% calibrated over the entire measurement range for hydrogen

4. Conclusion

Two fundamental types of emissions sources are in the scope of NHyRA. Fugitive emissions (unintended) and vented (intended) emissions to the atmosphere. Emissions from combustion sources may present additional challenges, such as other products within the exhaust that may interfere with the measurement. All these emissions may diffuse over a large area, for example, from multiple small vents.

Emissions from large stacks and vents normally monitored by continuous emissions monitoring systems (CEMS) for pollutants are not considered, as developing the relevant standard methods and validation is likely out of this project's scope. Emissions from purged events (likely resulting in very high concentrations) are also out of scope since testing any prospective instruments and methods will require very stringent safety measures to be in place.

Techniques for monitoring hydrogen emissions have been categorised as follows:

- Detection of leaks at component level. Sniffers, passive sensors and acoustic cameras are candidate techniques for method development.
- Detection and quantification of leaks at component level. High-flow sampling is a candidate technique to consider for method development.
- Surveillance and/or quantification of emissions at area/site level. Distributed networks and tracers are candidate techniques to consider for method development.

Several instruments available on the market can measure hydrogen concentration, and the suitability of these to detect and/or quantify emissions sources will need to be assessed in the preceding WP2 stages. A spreadsheet lists specific instruments and their performance characteristics separately (List of hydrogen monitoring methods, instruments and emerging techniques_v2.xlsx). This spreadsheet will be updated as new instruments become available.

A good practice guide for hydrogen and hydrogen-enriched natural gas leak detection is now available, covering equipment, calibration, methods and validation [30]

Important factors to consider during the selection of instruments and sensors, development, test and validation of methods are: the gas composition of emission sources (for example, what effect does water vapour have on the measurement), what is the threshold for a leak?, effect of odorants on the monitoring method, review the type of emissions that are in scope which may depend on the instrument design and capabilities (for example, is it feasible with the scope of the project to develop a method for measuring pure hydrogen from a vent?), to identify the level of performance required for instruments to fulfil the requirements of testing and validation in work package 3.

ABBREVIATIONS

CEMS	Continuous Emission Monitoring System
DIAL	Differential Absorption Lidar
EPA	Environmental Protection Agency
FEDS	Fugitive Emissions Detection System
FET	Field Effect Transistor
GWP	Global Warming Potential
MOS	Metal Oxide Semiconductor
NMVOC	Non Methane Volatile Organic Compounds
NPW	Negative Pressure Wave
OGI	Optical Gas Imaging
PPA	Point Pressure Analysis
RTTM	Real-time Transient Model methods
SOF	Solar Occultation Flux
TCD	Thermal Conductivity Detector
TRL	Technology Readiness Level
VOC	Volatile Organic Compounds
WP	Work Package

GLOSSARY

Table 5. General and metrological lexicon.

Calibration	An operation that, under specific conditions, establishes a relationship between the quantity measured (with uncertainties) and a traceable measurement standard (with uncertainties) [9].
Concentration	The amount, or abundance, of a particular chemical constituent divided by the total volume of the mixture. Concentration may be expressed in units of mass or moles per unit volume (e.g., µg m^{-3}, mol dm^{-3}). Concentration is often used interchangeably with amount fraction.
Coverage factor (interval)	Interval containing the set of true quantity values of a measurand within a stated probability.
Detection limit	The lowest signal that can be reliably detected with a sufficient degree of confidence (sensitivity). Also referred to as the limit of detection. The analytical or technological detection limit may differ from the method detection limit.
Measurand	The physical quantity subject to measurement [9].
Measurement	The process of determining a physical quantity [9].
Measurement uncertainty	A non-negative parameter which characterises the dispersion of measurement results attributed to a measurand [9].
Quantification	Determination of mass emission rate of an emission.
Quantification limit	Minimum quantifiable emissions, based on the uncertainty of the method.
Reconciliation	The act of making measurements comparable and compatible with each other, for example, across a range of spatial or temporal scales.
Resolution	The smallest change in a quantity being measured that causes a perceptible change in measured value [9].
Sensitivity	The ratio of the change in the measured value to the corresponding change in the value of the quantity being measured [9].
Traceability	A property of a measurement result whereby the result can be related to a reference through a document unbroken chain of calibrations, each contributing to the measurement uncertainty [9].
Uncertainty	See **Measurement uncertainty**
Validation	The assurance that a product, service, or system meets the required needs of the customer and other identified stakeholders [9].
Verification	The evaluation of whether a product, service, or system complies with a regulation, requirement, specification, or imposed condition [9].

Table 6. Terms and definitions.

Italics and bold – aligned with terms defined in work package 1.2

Area	Area emissions are releases to the atmosphere from an extended area; for example, the surface of a wastewater pond.
Component	Part or element of a larger whole, e.g., flange, valve, connection.
Continuous emission	An emission that occurs continuously for a period greater than a prescribed threshold. The threshold (for example, 24 hours) should be defined. The emission rate may vary.
Detector	Indicates the presence of a phenomenon, body, or substance when a threshold value of an associated quantity is exceeded [9].
Elevated (source type)	Elevated emissions are releases to the atmosphere from a source that is at height above ground, for example stack or flare. Ideally, the approximate height should be defined.
Emission rate	The rate of emission of a specific chemical species, typically to the atmosphere. The emission rate is typically measured in units of mass (or moles) per unit time (e.g., g s^{-1}, kg $hour^{-1}$).
Equipment	Asset, device or component of a hydrogen system depending on the considered granularity.
Emission factor (EF)	Factor that describes typical H2 emissions of a component or part of the system (e.g., valve, pipeline section) or from an event and can have units like [kg/km] or [kg/event].
Hydrogen system	Any plants or archetypes defined in Task 1.1 and implemented in a H2 supply chain section, e.g., production, storage, conversion, transportation and, end uses.
Emission quantification	Activities to determine the quantity of emissions by means of direct measurements or, where direct measurements are not feasible, based on other methods such as simulation tools, and other detailed engineering calculations or a combination of such methods.
Functional element	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	Leakages due to tightness failure and permeation.
Incident	Unexpected occurrence, which could lead to an emergency situation.
Incident emission	Hydrogen emissions from unplanned events.
Incomplete combustion emission	Unburned hydrogen in the exhaust gases from natural gas combustion devices, such as turbines, engines, boilers or flares.
Operational emission	Hydrogen emissions from normal or planned operating activities.
Permeation	Penetration of a permeate (such as a liquid, gas, or vapour) through a solid.

Leak rate	Colloquially used as a replacement for emission rate, often with regards to an emission source which is not expected to be emitting under normal circumstances (i.e., a fugitive emission source), such as a natural gas pipeline.
LDAR	Leak detection and repair. A process in which a leaking component is identified and located prior to the leak being scheduled for repair [31]
Instrument	A device used for making measurements which consists of a sensor or a detector.
Method	A generic procedure or a set of instructions (either prescribed or guidance) employed for scientific measurement. In the case of emission monitoring, the method refers to a combination of a measurement technology, a sampling strategy, and an emission rate calculation or model. A method should describe the scope, protocol, and relevant metrological factors to provide evidence that the method can produce data which can be trusted (for example, evidence of method validation). A method will consist of a measurement instrument, sampling strategy and emissions quantification element (if reporting emissions rate) or suite of complementary method elements.
Monitoring	A generic term used to describe the estimation, 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.
Open path	Open-path optical spectroscopy is used to measure the concentration of a chemical species across a path length across free space within the atmosphere.
Passive	Optical spectroscopy which uses ambient light (such as sunlight) as a light source.
Periodic	A periodic report with a defined period (or frequency).
Point (source type)	Point source emissions are those arising from a specific localised release, such as a vent stack. In practical terms a point source is one giving rise to a narrow plume of emissions (from the perspective of the monitoring method).
Point-sensor (sampling strategy)	A point-sensor has to be deployed in the measurement area and typically provides a much smaller coverage area
Remote-sensing (sampling strategy)	Remote-sensing (also referred to as standoff detection) involves the measurement of the properties of an object without making physical contact with that object. In the case of emissions measurement, the object is typically understood to be the emission plume. Therefore, a method which uses remote-sensing does not need to be physically located within the emissions plume (or even in the region where emissions may occur). The opposite of remote-sensing is referred to as a point measurement system (or in-situ sampling), and which needs to be physically located within the plume, or within the target region.
Sampling strategy	Describes how the measurement is collected and represented, and the platform used.
Sensor	An element that is directly affected by the phenomenon, body, or substance carrying the quantity to be measured

Site	All sources within a physical unit. A site can be a steam methane reforming plant, an electrolysis plant, a compressor station, a hydrogen pipeline segment, liquified hydrogen terminal, a storage plant, etc.
Source	Component within a process or equipment that releases H2 to the atmosphere either intentionally or unintentionally, intermittently or continuously.
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).
Technique	A generic term used to describe a type of measurement instrument, sampling strategy, emissions quantification, or data process.
Vented emission	Gas released into the atmosphere intentionally from processes or activities that are designed to do it, or unintentionally when equipment malfunctions or operations are not normal.
Venting	Operational release of gas into the atmosphere.

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ANNEX 1: LIST OF INSTRUMENTS

A Full list of instruments and emerging techniques (and their intended applications) are provided in the following spreadsheet and a place holder for established methods. It is intended that this is a working document, to be updated on a periodic basis (frequency to be agreed)

Refer to the spread sheet reported at the end of this report.

ANNEX 2: EMERGING TECHNIQUES

This section lists techniques that are emerging techniques and likelihood of them being available for deployment during the period of this project.

1. Computational algorithms

Another group of methods for detecting leaks are methods that use input data such as gas flow, pressure, temperature, and appropriate computational algorithms to detect leaks [A1][A2]. This group of methods can only be used for gas networks transporting pure hydrogen or mixtures of hydrogen and natural gas. The application of computational methods to other elements of the value chain is limited due to the lack of continuous measurement of custody transfers. Calculation methods for leak detection are:

- **Basic methods** belonging to this group are those based on mass flow or volume balance at the input and output of the pipeline section under investigation [1][2][3].
- **Real-Time Transient Model methods** (RTTM) is improvement on the mass flow rate or volume balance-based method. This method allows compensation for dynamic changes occurring in the pipeline [1][2].
- **Negative Pressure Wave** (NPW) is a popular method to detect the occurrence and location of leak incidents in oil/gas pipeline [4]. This method uses negative pressure wave propagation from the leak site to measurement points both up- and downstream located below and above the leak.
- **Point pressure analysis** is based on the assumption that if there is a leak on a pipeline, the gas pressure in the pipeline decreases[1][2]. This method requires continuous pressure measurements at various points along the gas pipeline [3][5].

The advantages and disadvantages of individual leak detection computational methods are presented in Table A1 [3].

Table A1, advantages and disadvantages of individual leak detection computational methods

Methods	Advantages	Disadvantages	Perspectives for addressing disadvantages
Basic methods	Low-cost, Prompt leakage detection	Unable to locate leakage	Combining with another method capable of leakage localization
Real-time transient model methods	Capability for verifying the proper operation of the sensors on the pipeline Ability to predict the possible location of future leakage by performing high accurate calculations	Requires high computational power for accuracy in calculations Need to spend much time detecting and localizing small-scale leaks The high complexity of the appropriate RTTM development process	Using intelligent algorithms coupled with this method to reduce the computational costs
Negative Pressure Wave	Smooth operation in setup and performance Online leakage detection with satisfying precision	Sensitivity to environmental noise leads to poor leakage localization Inability to detect low rate leakages in the standard version of this technique	Development of methods that reduce the impact of environmental noise Development of methods for correct estimation of low leakage rate
Pressure Point Analysis	No requirement for a particular model or program for leakage detection	Need for installation of a large number of pressure sensors Inability to localize leakage Inability to accurately detect leakage in transient conditions Inability to accurately estimate the leakage rate High negative impact of environmental noise on leakage localization	Use other methods coupled with this method to reduce the high false alarm rate

2. Distributed low cost sensors – area and site level quantification

Currently there are no developed techniques or methods that can survey (detect and localise) emissions and quantify emissions efficiently over a large areas and provide continuous time coverage. The two aforementioned techniques have inherent limitations:

- Distributed sampling has limited spatial coverage due to the logistical challenges of deploying tubes across a site and provides near-continuous coverage.
- Tracer only provides a snapshot in time.

NPL are investigating whether low-cost sensors can be used to complement the FEDS (distributed sampling) to improve its temporal and spatial coverage and hence provide continuous coverage and enhanced spatial coverage of a site for hydrogen. This is current part of an active research project at NPL, currently low TRL.

There are sensor based solutions being developed for methane and/or air quality applications, for example [6][7][8]. The development of standards to test, select and deploy low cost sensors (for air quality applications) is a rapidly developing area [9][10]. Further studies are required to investigate the applicability of these systems and standards to hydrogen monitoring.

3. RAMAN: Spectroscopic

Another area being investigated to survey and/or quantify large areas is using spectroscopic techniques. Methane and NMVOCs monitoring use absorption spectroscopy, example techniques are Optical Gas imaging (OGI), Differential Absorption Lidar (DIAL) [11] and Solar Occultation Flux (SOF) [12]. However, for hydrogen there would be limited absorption of hydrogen in the infrared, such techniques are not available for monitoring hydrogen, therefore alternative techniques such as those that could exploit Raman spectroscopy [13] would need to be considered. OGI, DIAL and SOF have the advantage of being able to *remotely sense* emissions and being able to monitor over greater spatial distances compared to sniffers. One could envisage a Raman based technique that operates in a similar way to DIAL, refer to Figure A1, that could be used to acquire 'snapshot' measurements of functional elements and whole sites, this covering the lower right-hand side of the map shown in Figure A1.

This is current part of a research project at NPL, currently low TRL.

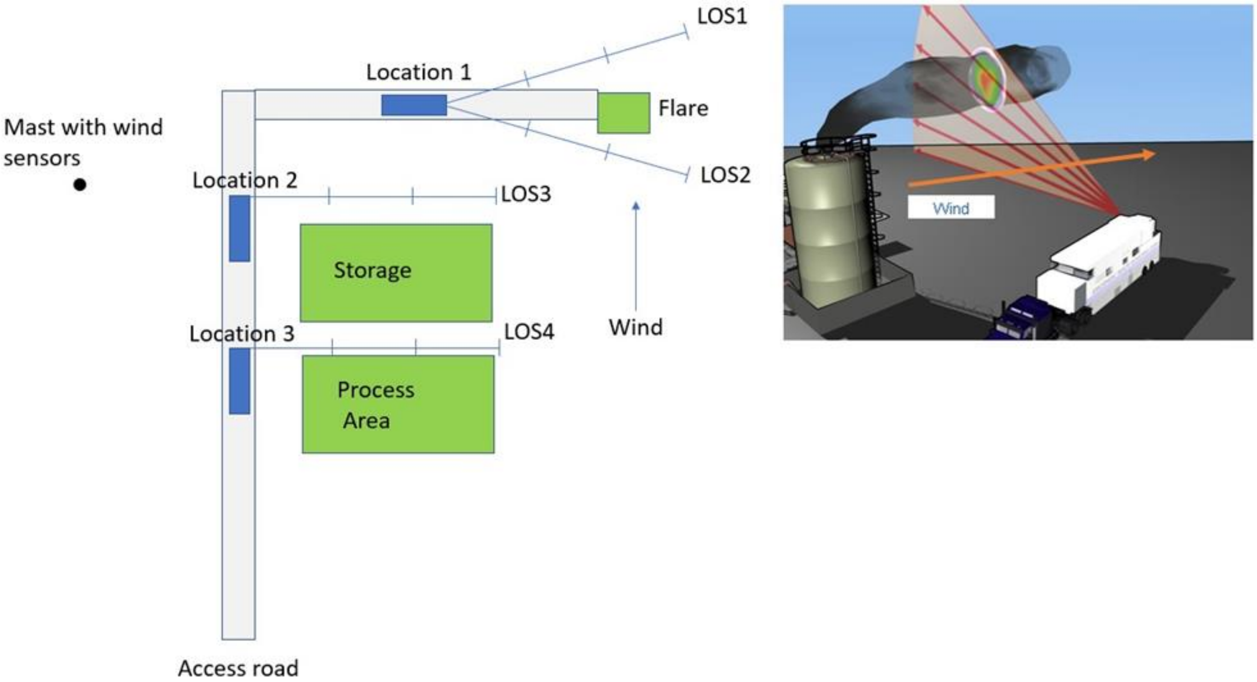

Figure A1, Sketch of a concept optical system

ANNEX 3: OTHER TECHNOLOGIES

The following technologies were investigated during the literature search, but are unlikely to be suitable for further reconsideration:

- Thermoelectric (a type of catalyst sensor).
  This kind of sensor are made of a thick film (usually a Nickel Oxide (NiO) or Lithium-doped Nickel Oxide) which serve as a base, over half of this surface a thin Platinum (Pt) film is deposited as a catalyst. In presence of oxygen (air), when this sensor is exposed to molecular hydrogen a catalytic exothermic reaction occurs, releasing heat only in the platinum-coated surface. Then a thermo-electrical voltage builds up along the hot (Pt) and cold (just NiO) regions of the oxide thick film sensor. This strategy allows to measure relatively high concentrations of hydrogen, from 0.025 to 10% in air with a good linearity response.

  No recent versions of the use of this technology were found to be commercial available

- Laser Spectroscopy and standard Infrared. Hydrogen does not respond to standard laser absorption while portable Raman spectrometers for hydrogen are not commercially available and their development is immature.

- Optical sensors. Sensitive to cross interference from flammable gases and even affected by ambient light and to temperature changes, so likely to be unsuitable for in field monitoring.
  Based on optically active materials. They have the potential for operation in explosive atmospheres because generally they are electrically isolated [14]. There are many types of optical sensors, the most common are those based on the optical properties of palladium films. The exposure to hydrogen produces a dimensional change in this metal, modifying its effective optical path, which is proportional to the hydrogen interacting with the Pd film which in turns is proportional to the H2 concentration. Interferometric or reflectivity techniques are employed to measure this dimensional change.

In addition to the technologies already mentioned, there are several other kinds of hydrogen sensors, such as the sound-resonance hydrogen sensor [15] and Surface Acoustic Wave and Microresonance-Based Sensors [16] and mechanical sensors [14]. However, as far as we know there are no available commercial detectors based on these technologies.

ANNEX 4: REFERENCES

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Page 1: Instrument performance – from manufacturers datasheet

		Instrument performance (not yet independently tested/ determined)									
Manufacturer	**Model**	**Spatial**		**Temporal**		**Measurand (gas concentration)**					
		Resolution (m)	**Range (m)**	**Time required to report a measurement (s)**	**Response time (s)**	**Intended Species**	**Sensitivity**	**Precision**	**Accuracy**	**Range**	**Displayed units**
Riken Keiki	GP 1000	N/A	N/A		90% response in 30s	Combustible gases (such as methane, hydrocarbons, hydrogen etc.)			"+/- 5% of full scale"	0 to 100% LEL	%LEL
Riken Keiki	GX Force	N/A	N/A								
Riken Keiki	NP 1000	N/A	N/A		90% response in 30s				"+/- 5% vol%"	0 to 100% vol%	vol%
Inficon	Extrima	N/A	N/A		Not available	Hydrogen					
Inficon	Sentrac Strix	N/A	N/A		"@10ppm" 0.6s						
Inficon	XL 3000	N/A	N/A		1s						ppm
Teledyne	GS 700 - Hydrogen	N/A	N/A		2s per metre of tubing	Hydrogen (includes an infrared sensor for methane)					
Process insights	TIGER OPTICS™ HALO™ H2 analyzer	N/A	N/A			Hydrogen specific					
Distran	Distran Ultra Pro X (ultrasonic camera)										
Sensit	HXG-3/3P	N/A	N/A								
AP2E	(need to investigate their different products)	N/A	N/A								
Pfeiffer	ASM340	N/A	N/A								
Horiba	HyEVO	N/A	N/A								
Asea Brown Boveri	EL3060 / A0200	N/A	N/A			Various					
Ametek	TA5000	N/A	N/A								

Peak Laboratories	(need to investigate their different products)	N/A	N/A								
Ecotec	E300	N/A	N/A								
Asystom	Sentinel EX			1 min							
Honneywell	searchzone sonik	Basic Mode, 50 dB setting = 12 m Profile Mode (4 dB above background) = 20 meters			Instantaneous						
Fluke	Fluke ii910 (ultrasonic camera)										

Page 2: Instrument characteristics – from manufacturers datasheet

Manufacturer	**Model**	**Sample inlet (sniffer only)**		**Physical (manufacturers datasheet)**							
		inlet pressure	**sample flow rate**	**Size (w,l,h) cm**	**Weight (kg)**	**Power source**	**IP rating**	**Explosion proof class**	**Operating temperature range**	**Operating humidity range**	
Riken Keiki	GP 1000			8 x 3.6 x 12.4	0.3	Battery	IP 67	IECEx and ATEX (see datasheet)			
Riken Keiki	GX Force			6.4 x 4.7 x 17.3	0.3	Battery	IP 67	IECEx and ATEX (see datasheet)			
Riken Keiki	NP 1000			8 x 3.6 x 12.4	0.3	Battery	IP 67	IECEx and ATEX (see datasheet)			
Inficon	Extrima				4.5	Battery	IP 67	yes (standard?)			
Inficon	Sentrac Strix	Atmosphere	passive (no pump)	20 x 33 x 28	4	Battery	IP 30	No			
Inficon	XL 3000	Atmosphere	3L /min or 0.3 L /min	55 x 41 x 36	38	220Vac 50Hz	None	No			
Teledyne	GS 700 - Hydrogen	Atmosphere	0.5L /min	19 x 10 x 11	1.3	Battery	IP 55	yes (standard?)			
Process insights	TIGER OPTICS™ HALO™ H2 analyzer			Desktop							
Distran	Distran Ultra Pro X (ultrasonic camera)			portable							
Sensit	HXG-3/3P	N/A sensor - no sampling pump	N/A sensor - no sampling pump	portable							
AP2E	(need to investigate their different products)			Desktop							
Pfeiffer	ASM340			Desktop							

Horiba	HyEVO			Desktop							
Asea Brown Boveri	EL3060 / A0200			Desktop							
Ametek	TA5000			Desktop							
Peak Laboratories	(need to investigate their different products)			Desktop							
Ecotec	E300										
Asystom	Sentinel EX										
Honneywell	searchzone sonik			Module: 112 x 86 x 42 mm. Extension probe: Ø35 x 20 mm		10-30 VDC	IP66	ATEX/IECEx Zone 1	-40 °C to +58 °C	5% to 95% RH, non-condensing	
Fluke	Fluke ii910 (ultrasonic camera)			313 x 131 x 119 mm			IP65/66/67	ATEX II 2G Ex db [ia] IIC T4 Gb			

Page 3 Weblinks to datasheets

Manufacturer	Model	Weblink to datasheet
Riken Keiki	GP 1000	Portable Gas Detector GP-1000 | Category Search | RIKEN KEIKI CO., LTD.
Riken Keiki	GX Force	Portable Gas Detector GX-Force | Category Search | RIKEN KEIKI CO., LTD.
Riken Keiki	NP 1000	Portable Gas Monitor NP-1000 | Category Search | RIKEN KEIKI CO., LTD.
Inficon	Extrima	XL3000flex | INFICON
Inficon	Sentrac Strix	Sensistor® Sentrac® | INFICON
Inficon	XL 3000	XL3000flex | INFICON
Teledyne	GS 700 - Hydrogen	GMI Gasurveyor 700 (GS700) - Portable Infrared Gas Leak Detector | Teledyne GFD (teledynegasandflamedetection.com)
Process insights	TIGER OPTICS™ HALO™ H2 analyzer	HALO H2 PPB-Level Hydrogen Analyzer (process-insights.com)
Distran	Distran Ultra Pro X (ultrasonic camera)	Hydrogen leak detection: ensure safety with Distran Ultra Pro X
Sensit	HXG-3/3P	SENSIT® HXG-3 Combustible Gas Leak Detector (gasleaksensors.com)
AP2E	(need to investigate their different products)	ap2e - ProCeas - EN - Ap2e
Pfeiffer	ASM340	ASM 340 | pvcp (pfeiffer-vacuum.com)
Horiba	HyEVO	HyEVO Hydrogen Gas Analyzer - HORIBA
Asea Brown Boveri	EL3060 / A0200	Hazardous Area Gas Analyzer | Manufacturer | Supplier - Extractive Gas Analyzers | Supplier | Manufacturer (Analytical Measurement | Products | Instruments | Equipment) | ABB
Ametek	TA5000	ta5000 Gas Analyzers (ametekpi.com)
Peak Laboratories	(need to investigate their different products)	Peak Laboratories | Peak Performer 1 RCP (Reducing Compound Photometer)
Ecotec	E300	

Asystom	Sentinel EX	https://www.asystom.com/fr/asystomsentinel-dispositifs-multi-capteurs/
Honneywell	searchzone sonik	Searchzone Sonik™ | Honeywell
Fluke	Fluke ii910 (ultrasonic camera)	

Page 4: Descriptions and intended or potential use

Manufacturer	Model	principle of operation and technology	Intended or potential application	Assumptions and limitations	Approx Price as of 2023	Autonomous <-> expert	Calibration process	Quality process	Point or remote sensing
						Example: "basic training"	Example "gas cell?"		
Riken Keiki	GP 1000	Catalytic combustion	Leak detection	Based on technology: Not selective for H2, cant operate in low O2					Point sensing
Riken Keiki	GX Force	Catalytic combustion	Leak detection						
Riken Keiki	NP 1000	Thermal conductivity	Leak detection	Based on technology: Not selective for H2					
Inficon	Extrima	Palladium alloy Field Effect Transistor (FET) sensor.	Leak detection or possibly integrated into a leak quantification system (e.g. Hiflow?)	No sampling pump					
Inficon	Sentrac Strix	Palladium alloy Field Effect Transistor (FET) sensor.			£13k				
Inficon	XL 3000	Mass spectroscopy	Reference instrument (testing/ validation)? or site level quantification (e.g. analyser within a distributed network?)	Desk based instrument and mains powered (not hand portable). Needs a suitable enclosure if outside	£24k				
Teledyne	GS 700 - Hydrogen	Catalytic bead sensor and thermal conductivity (for hydrogen) and IR (for methane).	Leak detection or possibly integrated into a leak quantification system (e.g. Hiflow?)		£3.5k				
Process insights	TIGER OPTICS™ HALO™ H2 analyzer	This instrument measures hydrogen concentration by combining oxygen and the sampled hydrogen over a catalyst to produce water. The resultant	Reference instrument (testing/ validation)? or site level quantification (e.g. analyser within a distributed network?)						

		water vapour is then measured using a laser-based Cavity Ring Down Spectrometer							
Distran	Distran Ultra Pro X (ultrasonic camera)	Acoustic camera	Leak detection						depends on the spatial range
Sensit	HXG-3/3P	Metal Oxide Semiconductor	Leak detection						
AP2E	(need to investigate their different products)	Optical feedback cavity enhanced absorption spectroscopy for hydrogen requires large scale instrumentation, is suited for continuous monitoring but not suitable as a portable device.	Reference instrument (testing/ validation)? or site level quantification (e.g. analyser within a distributed network?)						Point sensing
Pfeiffer	ASM340	Mass spectroscopy							
Horiba	HyEVO	Mass spectroscopy							
Asea Brown Boveri	EL3060 / A0200	Thermal conductivity for hydrogen							
Ametek	TA5000	Gas chromatograph	Out of scope?						
Peak Laboratories	(need to investigate their different products)	Gas chromatograph	Out of scope?						
Ecotec	E300	Mass spectrometer.	Reference instrument (testing/ validation)? or site level quantification (e.g. analyser within a distributed network?)						
Asystom	Sentinel EX	ultrasound	Leak detection						
Honneywell	searchzone sonik	ultrasound	Leak detection						
Fluke	Fluke ii910 (ultrasonic camera)								

Page 5: Instrument performance – based on laboratory / field testing – to be completed on wp2.2 onwards

Manufacturer	Model	Additional categories (based on laboratory and field testing)					
		Linearity range	Interferences		Requires O2?	Drift	
			methane	Water vapour		Short term	Long Term
Riken Keiki	GP 1000				Yes		
Riken Keiki	GX Force				Yes		
Riken Keiki	NP 1000				No		
Inficon	Extrima				No		
Inficon	Sentrac Strix				Yes > 15%		
Inficon	XL 3000				No		
Teledyne	GS 700 - Hydrogen				yes > 21%		
Process insights	TIGER OPTICS™ HALO™ H2 analyzer				Yes > 15%		
Distran	Distran Ultra Pro X (ultrasonic camera)						
Sensit	HXG-3/3P				Yes		
AP2E	(need to investigate their different products)						
Pfeiffer	ASM340				No		
Horiba	HyEVO						
Asea Brown Boveri	EL3060 / A0200						
Ametek	TA5000						

Peak Laboratories	(need to investigate their different products)						
Ecotec	E300						
Asystom	Sentinel EX						
Honneywell	searchzone sonik						
Fluke	Fluke ii910 (ultrasonic camera)						