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Review Article

Methods for detecting and quantifying hydrogen emissions over a wide range of temporal and spatial scales: a state-of-the-art review

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ABSTRACT

Hydrogen (H_2) is currently used in several industrial sectors. However, due to its potential contribution to climate neutrality, the H_2 market is expected to expand to other sectors in the near future. H_2 emissions pose a concern due to their potential influence on methane's atmospheric lifetime, therefore acting as an indirect greenhouse gas. Therefore, minimising H_2 emissions would reduce any environmental impact and enhance safety and efficiency of the H_2 value chain. Adopting measures to mitigate H_2 emissions requires data that can be trusted and are truly representative of the emissions being monitored. Such data require validated methods based on robust metrological principles. Standard methods are needed to detect and quantify emissions over a wide range of mass or volumetric ranges, spatial and temporal scales, and emission source types across the H_2 value chain. In addition, many instruments and associated techniques are available on the (and near to) market for detecting H_2 leaks or measuring its concentration, but their suitability depends on how the instrument is deployed and its technological performance. To date, no publication reviewing these aspects is available in the literature. To cover this gap, the present paper will provide a foundation for the future development of H_2 monitoring methods. The essential constituents of a method will be defined, an overview of different monitoring techniques provided, followed by a discussion on future method development. Examples of such monitoring techniques covered are sniffers, acoustic imaging and tracer correlation. It should be feasible to develop methods to monitor emissions at component level in the near future, while further technical development is required for methods that cover larger spatial scales.

Abbreviations

AI	Artificial Intelligence
AMS	Automated Measuring System
ATEX	Atmospheres Explosives
BSI	British Standards Institute
CEMS	Continuous Emission Monitoring System
CEN	Comité Européen de Normalisation
DAS	Distributed Acoustic Sensing
DIAL	Differential Absorption Lidar
DIN	Deutsches Institut für Normung
EPA	Environmental Protection Agency
FBG	Fiber Bragg Grating
FEDS	Fugitive Emissions Detection System
FID	Flame Ionisation Detector
GC	Gas Chromatography
GWP	Global Warming Potential
HFEDS	Hydrogen capable Fugitive Emissions Detection System
HRS	Hydrogen Refuelling Station

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IEA	International Energy Agency
ISO	International Organisation for Standardisation
JRC	Joint Research Centre
LEL	Lower Explosive Limit
LOS	Line Of Sight
MCERTS	Monitoring Certification Scheme
MOS	Metal Oxide Semiconductor
Mt	Mega Tonnes
NG	Natural Gas
NHyRA	pre-Normative Hydrogen Release Assessment
NMVOC	Non-Methane Volatile Organic Compounds
NREL	National Renewable Energy Laboratory
OGI	Optical Gas Imaging
OPTHYCS	Optic Fibre-based Hydrogen Control Systems
PT	Performance Test
TCD	Thermal Conductivity Detector
TRL	Technology Readiness Level
VOC	Volatile Organic Compounds

Symbols

CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
H_2	Hydrogen
NO	Nitrogen Oxide
NO_2	Nitrogen Dioxide
O_3	Ozone
OH	Hydroxyl
Pd	Palladium

1. Introduction

Interest in Green hydrogen (H_2) has grown rapidly as the energy sector shifts towards sustainable sources, driven by global efforts to tackle climate change and enhance energy security. Green H_2 could support the decarbonisation of several traditionally fossil-based energy and industrial sectors such as petrochemical [1], oil and gas [2], glass [3], chemical [4], steel making [5], and mobility [6]. Consequently, researchers also attempted to estimate future H_2 demand. For example, Nnabuife et al. [7] discussed the scenarios proposed by the International Energy Agency (IEA) reporting that 530 Mt would be needed to achieve a net zero emissions by 2050, i.e., 5.9 times the world annual demand in 2020 [8]. Focusing to Europe, most of the member states are working to draft, approve and publish a national H_2 strategy to support the EU target consisting in an annual production of 10 Mt by 2030 [9–11].

In recent years researchers started to investigate the role of H_2 emissions both in the stratosphere and troposphere as an indirect greenhouse gas [12]. As reported in the literature, almost 30 % of the emitted H_2 reacts with the hydroxyl (•OH) radical increasing the persistence of methane (CH_4) in the atmosphere [13]. Lakshmanan and Bhati (2024) also investigated the reactions of H_2 in the troposphere with •OH and ozone (O_3) confirming the negative impact of its emissions through the value chain [14]. The list of papers that estimate H_2 Global Warming Potential (GWP) is long. Table 1 provides examples of GWP values and uncertainties from literature. The values are as quoted in the cited references.

Despite the uncertainty in the GWP for H_2 emissions, it is commonly agreed that the amount of H_2 emissions across the value chain will be a key factor in the determination of the climate impact. Improved uncertainty in GWP in the estimate of H_2 is needed to be included in the methodology for calculating greenhouse gases emissions and to better determine the impact of H_2 emissions over the whole supply chain in the greenhouse gas emissions accounting methodologies [20].

Consequently, identifying H_2 emissions sources, quantifying them with low uncertainty and developing mitigation strategies to minimise H_2 emissions are recognised needs [18]. Some studies were published

Table 1
List of GWP values and uncertainties from literature.

GWP of 20 years (equivalent tonnes of CO_2)	GWP of 100 years (equivalent tonnes of CO_2)	Reference
40.1 ± 24.1	12.8 ± 5.2	Hauglustaine et al. (2022) [15]
33 with an uncertainty range of 20–44	11.5 ± 5	Warwick et al. (2025) [16]
n/a	Ranges from 3.3 to 12.8 to 7.1 to 9.3 Best estimate 8 ± 2	Derwent (2023) [17]
n/a	11.6 ± 2.8	Sand et al. (2023) [18]
28^{+18}_{-11}	10^{+7}_{-4}	Chen et al. (2024) [19]

Note: n/a means data not provided in cited literature.

aiming to cover the research gap. For example, based on Warwick et al. estimations [16], Bertagni et al. [21] indicated a threshold for emissions up to 9 ± 3 % of the total H_2 demand as an upper limit to avoid a negative effect. Warwick et al. [22], assuming a GWP100 equal to 12 ± 6 and a H_2 market covering about 23 % of current demand, estimated that an emission equal to 1 % or 10 % of the demand would be equivalent to 110 and 1140 Tg CO_2 per year, respectively.

A shortcoming of the results derived from these studies is the availability of H_2 emissions data, which are limited in many cases to theoretical data and to a few technologies covering the H_2 supply chain. Some examples of the available sources in the literature are: Bond et al. [23], the Joint Research Centre (JRC) reports published in 2022 and 2023 [24,25], the report published by Frazer-Nash Consultancy in 2022 [26], the work of Copper et al. [27], Elizondo et al. [28] and the publication of the Oxford Institute for Energy Studies in 2024 [29]. However, in order to decrease the high level of uncertainty of H_2 emissions data, validated measurements are needed, and this will lead to improved understanding of the potential environmental impacts of H_2 emissions.

Measurements are also needed to understand emission sources so that mitigation strategies can be successfully implemented, and to report emissions and track reductions using inventories. As well as climate - safety, energy supply efficiency and security are drivers that will instigate emission monitoring, for example as part of leak detection and repair programmes.

Methods are needed to detect and quantify emissions over a wide range of mass or volumetric ranges, spatial and temporal scales and emission source types across the supply chain. Such methods must be underpinned by robust metrological principles to ensure that data can be trusted.

There are standard methods in place covering testing and use of systems that monitor H_2 emissions for safety purposes, e.g., ISO 26142:2010 [30], EN 60079-29 [31–33] and ISO/TR15916 [34]. However, there is a lack of guidance on monitoring emissions that don't pose a safety risk, i.e., emissions that generate lower concentrations than the Lower Explosive Limit (LEL). In addition, there are many guidance frameworks [35–38] and standards [39–41] used to monitor NG and pollutants that could be as a basis for developing new standard methods for H_2. There are many technologies that can measure H_2. However, there is no comprehensive review of how different techniques could be utilised and developed into metrologically robust monitoring methods, with coverage of the spatial and temporal monitoring space in mind.

To cover these gaps, this paper will provide a foundation for the future development of H_2 monitoring methods by providing:

- A definition of the essential constituents of a monitoring method from a metrological perspective, that could be used as a basis for developing new methods in section 2.
- An overview of monitoring techniques that utilise commercially available instruments and techniques that are in the concept stage in section 3.

- A discussion about future method development in section 4.

Definition of terminology used in the paper are provided in Tables 7 and 8 in the supplementary section.

2. H_2 monitoring methods

2.1. Definition of a method

A measurement method is defined as a generic description of a logical organisation of operations used in a measurement [42]. The term 'method' is widely used within the NG and H_2 sectors and often instruments or techniques are colloquially referred to as methods. If a monitoring method is to be used to provide trusted data, then it is important to define in detail what a method is and should consist of. A more detailed definition has been addressed in CH_4 monitoring [43]. In this definition the method refers to a combination of an instrument (or complimentary suite of instruments) and if relevant a means to determine mass emissions/leak rate and the definition of the following:

- Scope, including: a clear definition of the physical magnitude to be measured (e.g., gas concentration, emission rates) and its uncertainty, whether the method is to undertake direct measurements or estimations (e.g., based on models) and the emission types under investigation.
- Measurement objectives that describe how the measurement has to be performed and an established set of procedures that detail the planning, preparation, implementation of undertaking the measurements.
- The sampling strategy that indicates how the data are collected, assimilated, and reported.
- The metrology factors that include evidence of validation and conditions under which the tests were performed, including calibration and traceability, applicable standards and a quality system to provide confidence in data.
- Training and competencies.
- Limitations, dependencies and assumptions.
- Recommended instruments and techniques and the performance and evaluation requirements for instruments.

The aim is to develop a standard method that consists of the factors listed above. In this paper the term 'method' is distinguished from 'technique' which is used more informally to describe a type of an approach to detect or quantify H_2. This paper focusses on measurement-based methods (that may include modelling) as opposed to methods that use engineering calculations alone or emission factors to quantify emissions.

The properties of a monitoring method are obtained by validation and are to determine whether it can meet the data and quality reporting objectives. The properties of a method are typically: its uncertainty, detection limit, quantification limit (if applicable) and range of measurement or detection. However, a method's performance indicator (such as uncertainty) may be dependent on specific conditions (such as distance from the emission source, local wind speed, or other local conditions), therefore the conditions under which the method is validated must be clearly stated. If the method is intended to be used outside these conditions, then a specific validation test series encompassing the new conditions should be undertaken before its use in monitoring activities. It could lead to identify the limits of applicability of a given the method, which could be not suitable for some specific objectives or cases.

2.2. The choice of monitoring method

Once validated in realistic conditions, emissions monitoring aims to achieve one or more of the following:

- Provide data for regulatory compliance such as, for example, as made by undertaking a series of targeted measurements and then combining them into a site total.
- Identify and locate emissions aiming to implement mitigation strategies (e.g., repairs) for their reduction.
- Validate emission estimates derived from engineering calculations.
- Define emission factors [44], for example, of specific components from activity data and measurements.
- Carry out exploratory monitoring to better understand the characteristics of emissions as input for the definition of data reporting requirements.

Once the purpose has been identified, the choice or specification of a monitoring method (and its associated instruments) is a compromise between the cost and availability of instrumentation and meeting the data reporting and quality objectives and will be based on the characteristics of the emissions source.

2.2.1. Data reporting and quality objectives

Specifically, data reporting requirements define *what* needs to be detected (i.e. the subject), measured (i.e. physical quantity/es) and/or reported and definition of the data quality metrics, categorised as follows: spatial/temporal granularity, measurand characteristics and other requirements (e.g., aspects that describe the measurement site and the monitoring process, and any applicable regulations or standards that need to adhered to), refer to Table 9 in the supplementary material.

2.2.2. Emission source type and any known characteristics of the emissions source

To date no standardised categorisation or terminology exists for H_2 emissions. So, a potential approach is the use of Natural Gas (NG) terminology and categorisation as reported in Table 2 which is derived from Marcogaz [44,45]. Such a table should be included in an emissions inventory along with a description of the physical properties of the emissions source(s) (e.g., the physical area that the source covers; height of the source, temperature of the existing plume from a stack) and emission properties (e.g., gas composition: pure H_2 or blended CH_4/H_2; temporal characteristics: continuous or discontinuous emission). Whilst developing a method, it is important to define what emissions scenarios (i.e., categories and subcategories listed in the table) are in scope.

To the best knowledge of the authors, to date no studies provide guidelines on choice of method starting from the different types and characteristics of emissions sources specifically for H_2. For example, detecting fugitive emissions from small sized components as part of a leak detection and repair program will require a different approach (i.e., choice of instrument and monitoring methodology) to quantifying and reporting emissions covering a whole site to an industry regulator.

There is general guidance available in the NG sector, for example: GTI Energy has defined a set of protocols [35] that describe how to take measurements, process data, and apply an assurance process to all segments of the NG supply chain, Oil and Gas Methane Partnership (OGMP) technical guidance documents [37], and The Methane Guiding Principles partnership has published a number of best practice guides including identification, measurement, and quantification [38]. While these could conceivably be applied in general to H_2, methods will need to address the challenges specific to H_2.

2.3. Detection and quantification

Detection of H_2 emissions consists of the process of identifying the presence of H_2 considered to be above some defined threshold that is above the detection limit of the 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

Table 2
H_2 emissions per category. A not exhaustive list of examples is reported in the right column.

Types of emissions	Category	Subcategory	Examples (not exhaustive)
Fugitives	Leaks due to connections/loss of tightness	Leaks typically due to changes in conditions[a]	Leaks of flanges, seals, joints, valve seats
	Permeation	Wall permeation	Emissions from tanks or pipeline wall
		Subsurface emissions from a storage reservoir to the atmosphere	Emission from a geological reservoir
Vented	Operations	Purging/venting for works, process, commissioning and decommissioning	Works, maintenance, renewal
		Regular emissions of devices	Pneumatic emissions actuators, flow control valves, measurement equipment, compressor seals.
		Starts & stops	Emissions from start and stops of compressors
		Boil off – evaporation	Leaks due to overpressure caused by evaporation of liquid H_2
	Incidents	Leaks due to unexpected, sudden changes in conditions	Leaks due to third party damage, construction defect/material failure, ground movement, incorrect operations
Incomplete combustion			Unburned H_2 in exhaust gases from combustion devices

[a] These leaks include all the potential emissions occurring along the time due to, for example, materials degradation, damages caused by, for example, static or dynamic loads but also connection/loss of tightness due to permanent conditions.

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 tables. Alternatively, some techniques measure a quantity that infers the presence of a leak (e.g., acoustic intensity).

2.4. Instruments and sensors

A sensor is an element that is directly affected by the phenomenon, body, or substance carrying the quantity to be measured and then typically converts that into an electrical signal [42]. An instrument contains a sensor or array of sensors and processing to convert the electrical signal into a read out to the user, commonly using proprietary 'black box' software/firmware; if there is an insufficient understanding of the underlying mechanisms then understanding the instrument's performance can be challenging. There are many sensors, instruments and associated techniques (processes that may not necessarily follow a standard and subject to metrological rigor) available on the market (and near to market) for measuring H_2, but their suitability depends on how the instrument is deployed and its technological performance.

This paper is not meant to provide a comprehensive review of instruments and sensors as to date there are many reviews on H_2 measurement technologies. Examples are: comprehensive reviews and educational background [46,47], novel sensors [48], more focussed reviews that compare H_2 sensor technologies [49–52], sensor development programmes [53,54].

The National Renewable Energy Laboratory (NREL) laboratory has facilities for assessing the performance of H_2 sensors that are used in emissions quantification, characterising H_2 behaviour to optimise detection strategies for indoor, outdoor applications and large scale deployment applications [55]. The laboratory also has field-based facilities for testing and validating sensor performance to support specific application requirements and the development of codes of practice and standards [56–58].

2.5. Challenges

There are many challenges associated with undertaking H_2 monitoring of emissions, that is to either detect (i.e., to indicate the presence of an emission) or locate its presence or quantify an emission. Although the research field can draw upon the experiences in detecting and quantifying CH_4 from NG), H_2 is related to several challenges:

- Unlike CH_4 and many other species, H_2, has limited absorption in the infrared region, therefore the wide range of techniques based on absorption spectroscopy, including remote imaging techniques, that are available for NG would not be practical or cost effective for monitoring H_2, thus reducing the range of potential techniques that can be considered.
- Since H_2 is less dense than NG its dispersion properties may present significant challenges to the design of monitoring methods (e.g., location and spatial density of sensors, speed at which instruments are surveyed across components) and may also limit method scope.
- Since H_2 molecule is smaller than that of CH_4 in NG, therefore the number and severity of leaks occurring may be higher. This may have an impact on the design and implementation of monitoring protocols, e.g., sampling locations, monitoring priorities.
- The odorants used for NG are not suitable for H_2. The addition of new additives such as odorants could interfere with the monitoring process (i.e. at the sensor level).
- H_2 has a wide range of flammable concentrations, higher explosivity and lower ignition energy compared to NG [59], therefore specific controls to mitigate risk will be needed.

3. H_2 monitoring techniques

Monitoring techniques are categorised in four typologies:

1. Detection of leaks at component level.
2. Detection and quantification of leaks at component level.
3. Surveillance and/or quantification of emissions at area and site level.
4. Direct quantification of vented and ducted H_2 emissions and sources of combustion.

Fig. 1 illustrates the different temporal and spatial measurement scales involved in monitoring a site, similarly, as already defined for CH_4 [38]. 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 spatiotemporal area covered by the first two categories is shown in the lower left-hand portion of Fig. 1, while the third category is shown in the upper portion, and the fourth category is shown in the lower right-hand side. Methods within the first two categories detect and/or quantify emissions sources at the component level. Instruments associated with these methods are primarily designed to detect and/or measure gas concentrations from leaks, taken as "snapshots" or over periodic time intervals, for example, before and after a repair. Methods for the third

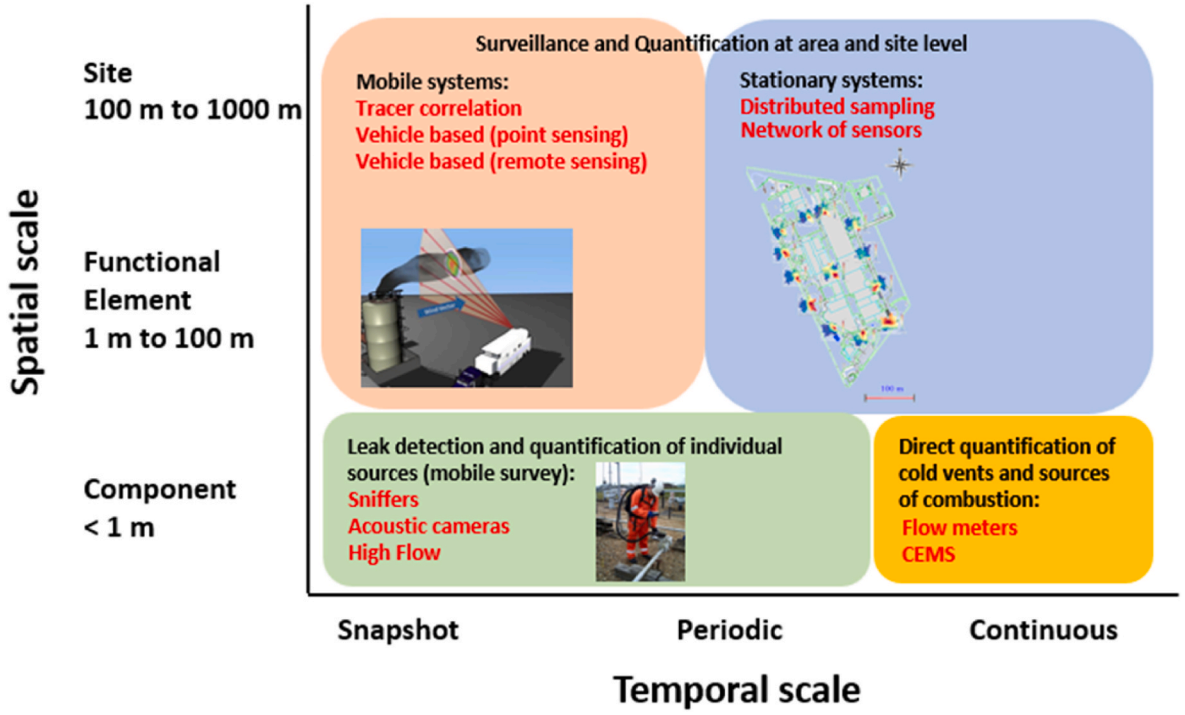

Fig. 1. Hydrogen monitoring temporal and spatial scales.

category detect and/or quantify emissions over a wide area (e.g., diffuse emissions from multiple sources), from functional elements to site level. Methods for the fourth category quantify emissions directly from a vent, ducts or sources of combustion. Where possible examples of commercially available instruments are given.

The monitoring techniques covered in this paper are only applicable to emissions that emanate from above ground equipment and installations. Underground or sub-sea pipes or storage such as salt caverns are not covered, although any above ground equipment associated with these would be included. The techniques covered here at component level are used to screen components individually by capturing a snapshot of their emissions.

There are established techniques that can monitor emissions continuously such as computational algorithms (based on engineering calculations) for detecting leaks based on gas flow, pressure and temperature of internal pipe conditions [60–64]. These techniques do not provide leak source location or determine whether there is a single or multiple leaks. There are emerging techniques that involve using fibre optic sensing and those that use Artificial Intelligence (AI).

Fiber optic sensing can be used to monitor pipelines or equipment for H_2 leak detection. These systems use pulsed laser light to measure physical parameters along the cable, enabling continuous monitoring from a single location. Different technologies that provide location of leaks can be used, such as Distributed Acoustic Sensing (DAS) to monitor acoustic waves, or localised sensing using H_2 sensitive coatings, for example Fiber Bragg Grating (FBG) with thin layers of Palladium (Pd), a technology that is currently under development [65]. These systems have advantages such as immunity to electromagnetic interference, safety in flammable environments, tolerance to high temperatures and passive operation so no power is needed along the components to be inspected [66]. The technologies are currently evolving to provide reliable leak measurement and quantification and minimise false alarm rates. Also, an analysis of sensor architectures, performance indicators, and the spectrum of sensing materials for hydrogen-sensitive materials coated on fibres has been reported [67]. There has been development of AI algorithms used to calculate or infer emissions from sensor measurements; for example: leak detection in pipelines [68] and the development of models to localise leaks in Hydrogen Refuelling Stations (HRS) [69].

The techniques chosen to be included in this section are readily used in the NG sector, therefore they should be considered for H_2. However, further efforts in providing validation data is highly encouraged.

3.1. *Detection of H_2 leaks at the component level*

This category covers the detection of fugitive emissions (leaks) by screening components on an individual basis, during activities such as leak detection and repair programs or preliminary surveillance for quantification.

3.1.1. *Sniffers and passive instruments*

Sniffers and passive instruments typically use 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, although currently most of them are specifically designed to work in these conditions. Sniffers are instruments where a sample of gas to be measured is directed towards a sensor by means of a generated air flow (internal pump). In passive instruments, instead, 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 data generated by the sensor to an output to the user. Furthermore, the emission plumes usually have complex geometries, are featured by a concentration gradient in the leak source surrounding space 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 (as well as its orientation relative to the plume), the features (shape and speed) of the leak being measured, the dispersion characteristics of H_2 and on the sampling rate of the internal pump. Table 3 lists typical sensor technologies. Each technology has a summary of their advantages and disadvantages to be considered for the selection of the sensor

Table 3
Advantages and Disadvantages of sensor technologies.

Advantages	Disadvantages	References
Catalytic combustion sensors		
• Resistant to changes in 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 (i.e., irreversible damage). • Low cost. • Ability to detect various gases, including H_2.	• 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. • Poor selectivity to H_2 (i.e., ability to discriminate H_2 from other gases). • Require Oxygen for combustion (maybe un-suitable for vented gases where there may be insufficient oxygen)	[70,71]
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. • No influence of humidity on sensor operation.	• Relatively long response time up to 2 min, compared to less than typically seconds for other types of sensors. • Susceptible to membrane 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.	[70–72]
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 highpower 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.	[70,71]
Palladium Alloy Sensors		
• Selectivity to H_2. • Fast response time. • Small physical size.	• Sensitive to changes in water vapour concentration (humidity) at low concentrations. • Not suitable for high concentration of H_2 (causes blistering). • Sensitive to Sulphur contaminants. • No linear response cause larger uncertainty at high concentrations • The sensors by themselves are difficult to source commercially.	[51]
Thermal Conductivity Detectors (TCD)		
• Fast response time. • Higher sensitivity for low molecular weight gases • Universal, it can analyse all possible gaseous species	• High detection limit: in the order of 1 % H_2 for some commercial sniffers. • Non selectivity.	[73]

technology based on the manufacturer's data or commonly held assumptions.

The following are example instrument products of each sensor type. This list is not exhaustive and is not meant to form any basis of recommendation.

- Catalytic: Riken Keiki GP 1000 and Teledyne GS 700H_2.
- Electrochemical: Riken Keiki GX Force.
- Metal Oxide Semiconductor: Sensit HXG-3/3P.
- Palladium Alloy: Inficon Extrima and Sentrac Strix.
- Thermal Conductivity: Riken Keiki NP 1000, and Teledyne GS 700H_2.

3.1.2. *Acoustic cameras*

Acoustic cameras are typically battery-operated handheld portable systems that detect the acoustic waves produced by the turbulence generated by a gas leak.

These ultrasonic imaging instruments are used for locating and characterising sound sources, producing a graphic-style sound display. This technology does not specifically measure H_2 concentration, but detect the presence of a gas leak. The acoustic properties of a leak will depend on the physical size and geometry of the hole through which the gas is escaping, the differential pressure (between inside the containment vessel/pipe 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 carried out from some meters to several tens of meters, depending on the size of the leak/emission. Acoustic cameras are less able to detect low velocity leaks or where line of sight to a leak is physically obscured. The output will be affected by acoustic reflections and ambient noise.

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 from the emissions source (depending on the sound level), 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.

3.1.3. *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 CH_4, 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 NG processes to detect large emissions at significant distances even if they are most commonly used to find small component scale leaks at less than 3 m from the equipment being monitored.

H_2, unlike CH_4, has limited absorption in the infrared region. Therefore, the OGI technique cannot directly detect H_2 leaks. However, interest in the possibility of using the OGI technique to detect leaks in the H_2 value chain resulted in the development of a technique using a tracer gas in the H_2. 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) [74], other tracers were searched in parallel [75]. Currently, Carbon Dioxide (CO_2) is a tracer added to H_2 that enables the OGI technique to detect leaks in the H_2 value chain [75–77]. This research has shown that adding CO_2 to H_2 below 5 % allows for effective optical imaging of gas leaks. However, the additions of CO_2 to H_2 streams may not be desirable for end-uses where H_2 purity is important (e.g., fuel cells).

3.2. *Detection and quantification of H_2 leaks at the component level*

This category covers the detection and quantification of fugitive emissions (leaks) of components on an individual basis. Typically, preliminary surveillance would be carried out initially using a leak detection technique. These types of methods are typically used for research (to understand emissions source characteristics), provide emissions data to compile an inventory of site emissions, to validate emission estimates derived from engineering calculations or to define emission factors from

activity data and measurements.

3.2.1. Direct quantification of leak rates: concentration with sampling flow rate measurement

An example is the High Flow method, as the HI FLOW ® sampler for quantifying NG, which has been successfully used for leak rate quantification in the NG industry for many years [78]. Leaking components are loosely enclosed using a dedicated adaptor, and a measured sampling flow of ambient air is drawn past the leaking component into the sampler. The resulting diluted concentration (inside the sampling system) is then measured by an instrument. A mass emission can be calculated using the measured concentration and sampling flow rate. A sampler is illustrated in Fig. 2. As far as the authors are aware there is no available method that has been validated for H_2, but in principle it should be feasible to develop a H_2 capable system that uses a commercially available instrument that measures H_2 concentration. It is necessary to capture the whole leak from the component being monitored, otherwise the quantified leak rate will be underestimated. This method requires direct access to the leak source location.

3.2.2. 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 [79]. 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 H_2). 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 H_2 leaks rates at industrial scale (in the order of litres per minute). Some applications include using a reference leak EN ISO 20485:2018 [80], although these are focused to relatively small leak rates (typically in the order of 10^{-5} to 10^{-3} L/min). 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 H_2 emissions.

Fig. 2. Example of a sampling method: Bacharach HI FLOW® sampler in operation.

3.2.3. Acoustic imaging

Some commercial acoustic detection devices include some functionalities to estimate the magnitude of an emission. Although in certain cases these could be used as a preliminary guidance, further work is needed to assess the performance of these devices to quantify leak rates. Most acoustic cameras allow estimation of the gas flow rate based on the sound source's loudness. Estimations of gas emissions in litres per minute can be obtained in real-time in some cases (having enough differential pressure). The accuracy of measurements and the limits of quantification are greatly influenced by ambient noise and other factors, in fact those figures are determined by the physical characteristics of the orifice from which the leak is escaping, such as its size, geometry and materials. The dimensions and geometry of the leak significantly affect the acoustic signal produced, and in real case leaks these are unknown parameters, limiting the applicability of this technology as a quantification method. Therefore, developing acoustic imaging to estimate emission rates would be very challenging. The pressure differential between the inside and outside of a system significantly affects the acoustic emission of a leak. Higher pressure differences result in more turbulent gas flow through the leak, generating stronger ultrasonic signals. Also, acoustic methods are difficult to use in the case of those elements of the H_2 value chain that are accompanied by noise, e.g., compressed H_2 refuelling stations. In addition, the spatial sampling and orientation of the camera relative to the leak will determine the measured result [81].

3.2.4. Indirect quantification: concentration with correlation curves

The standard EN15446 [39] 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) and then apply a response factor that represents the difference between the vapour being measured and the gas used for calibration. The second step is to determine the mass emissions rate by converting the concentration measurement into a leak rate by applying a correlation 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 [79]. However, all these factors are restricted to VOCs.

For H_2, no such correlations or emission factors exist; such data would need to be generated, compiled and validated if this approach were to be adopted.

3.3. Surveillance and/or quantification of H_2 emissions at area and site level

This category describes techniques that are in development to estimate emissions across a larger spatial area compared to components, i.e., from functional element to the whole site. Depending on the uncertainties of the methods that will utilise these techniques, 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. The first three techniques are mobile the last two are stationary.

3.3.1. Tracer method

Tracer gas dispersion is a technique 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 [82]. Work has been carried out to validate this method to quantify CH_4 emissions from area sources [83]. A tracer gas is released at a known concentration and flow rate. Thus, its emission rate is 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.

Measurement should be made whilst driving at an appropriate distance downwind of the area of interest to measure the concentrations of the target and tracer gases. Fig. 3 illustrates this technique.

For H_2, there needs to be further research to investigate the suitability of this technique. First, there is a need to investigate the transport of H_2 in the atmosphere in different scenarios (such as high and low leak rate) and identify a suitable tracer gas to match that of H_2, for which there should be no external sources near the target area and the measurement areas. Secondly, the limit of detection for this approach and the optimal distance for measurement downwind should be investigated. This is because the tracer gas dispersion technique typically utilise analysers with a detection limit (~1 ppb), so that measurements could be made at further distance downwind where both the target and tracer gases are well mixed. If the limit of detection is insufficient, measurements made further downwind would be dominated by noise. On the other hand, measurements made too close to the target area would be subjected to unknown systematic biases. Additionally, analysers with faster response time (~1 s) are preferable so that plume boundaries could be identified accurately. However, a slower analyser response time could be circumvented by driving at a slower speed or perform stationary measurements.

There are a number of analyser techniques that could be considered such as: Gas Chromatography [84], different types of spectroscopy or spectrometry: Optical Feedback Cavity Enhanced Absorption Spectroscopy [85], a novel H_2 to water vapour conversion followed by cavity ring down spectrometer that measures water vapour concentration [86], tuneable Infrared Laser Direct Absorption Spectroscopy [87,88] and mass spectrometry [89]. The method should define the instrument performance requirements. Typical performance specifications for the technologies mentioned are: concentration range (typically up to 500 ppm), limit of detection less than ~10 ppb (3σ).

In the frame of Equinor's Hydrogen Emissions Quantification project [90], Advanced Monitoring Solutions (adMS) has recently developed an ultrasensitive, highly precise (sub-ppb) mass spectrometry–based H_2 analyser, along with a new measurement strategy centred on the selection of tracer gases that present minimal environmental and climatic impacts. Demonstration trials have confirmed the effectiveness of these novel analytical approaches and a H_2 emission quantification study at a H_2 production and processing facility has been completed. A description of this system and recent test results are presented at the Norwegian Environmental Chemistry Symposium 2025, EGU 2025, and are due to be published soon.

3.3.2. *Mobile analyser based systems*

A vehicle and drone based technique for monitoring H_2 emissions has been developed [91], consisting of an AirCore sampling technique [92] with ppb-precision analysis by gas chromatography. The paper claims detection and quantification for the first time of small but persistent fugitive and vented emissions from an industrial setting, which could be applied across the H_2 value chain, including electrolysers, a H_2 fuelling station, and chemical production plants. Their emission estimates indicate current median loss rates at 1–2 %, up to 4.2 % at some times, of the estimated production and storage in these facilities. 4.2 % seems to be sufficiently large to urgently flag the need for monitoring and verification of H_2 emissions for the purpose of understanding climate change trajectory in the 21st century.

The Environmental Defence Fund (EDF) [93] have commissioned a H_2 emissions measurement study, which is a collaborative project between industry and academia. This study consists of multiple approaches: dual tracer release and a vehicle based analyser to measure concentration combined with reverse dispersion modelling to quantify emissions [94].

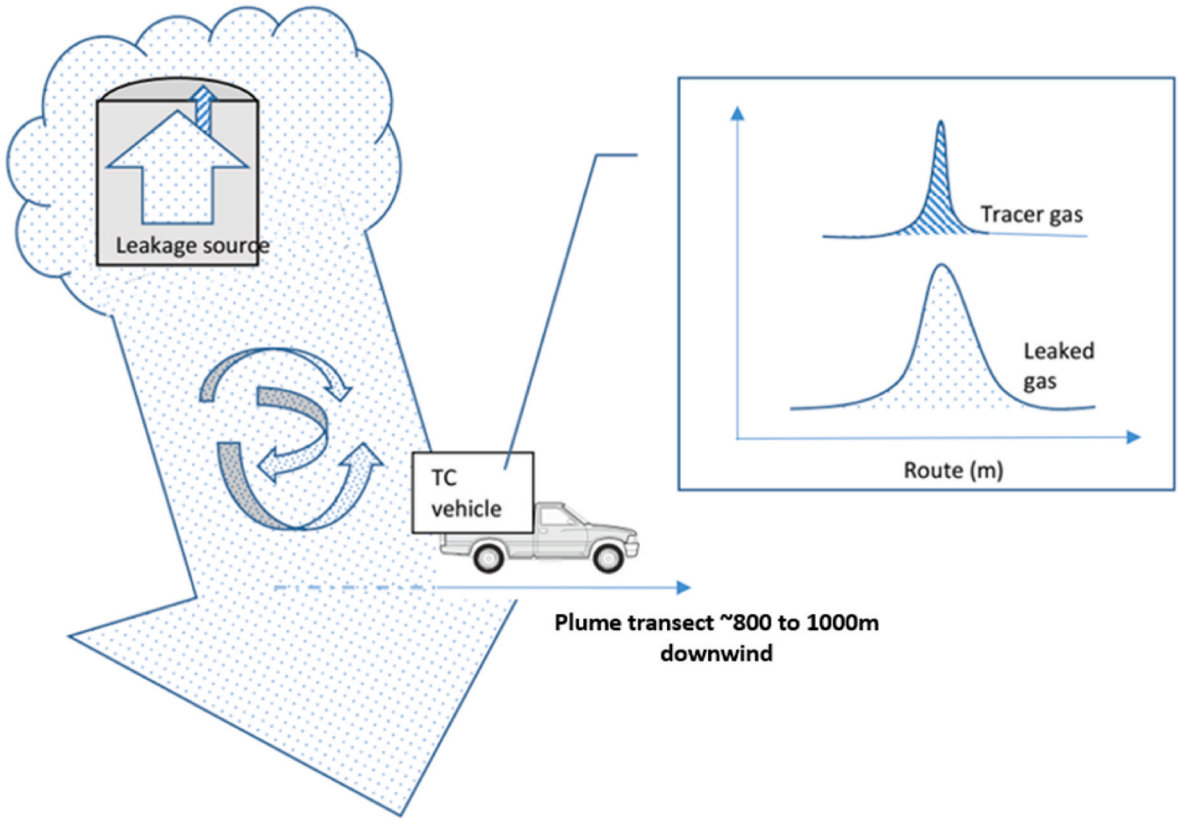

Fig. 3. Illustration of the tracer technique.

3.3.3. Mobile remote sensing based Raman spectroscopy

Remote sensing using spectroscopic techniques are widely used for the monitoring of CH_4 and NMVOCs, example techniques are Optical Gas imaging (OGI) and Differential Absorption Lidar (DIAL) [95]. OGI and DIAL have the advantage of being able to remotely sense emissions and can monitor over greater spatial distances compared to sniffers. However, since there would be limited absorption of H_2 in the infrared, these techniques are not suitable for the remote sensing of H_2.

H_2 detection by Raman scattering is an optical technique where the scattered light from a laser is shifted in frequency due to an inelastic scattering process and has the potential to be used for the remote detection of H_2 leaks. Work has been carried out by a number of researchers to develop this technique for the remote monitoring of H_2 [96–99] with quoted ranges up to 50 m, one area of concern to be able to deploy a system that can launch laser energy into the atmosphere that is eye safe.

It is envisaged that the use of Raman scattering for the remote sensing of H_2 leaks and potentially the quantification of H_2 emissions, will have some similarities to the application of differential absorption Lidar (DIAL) where a 2D vertical profile of the gas concentration is measured downwind of an area of interest, the concentration is combined with wind speed and direction measurements to calculate an emission rate. The technique is illustrated in Fig. 4, showing the deployed locations (1,2 and 3) to quantify emissions along a Line Of Sight (LOS) downwind of an area of interest. Further work would be required to assess how this technique could be deployed in a H_2 energy economy and in an industrial environment.

3.3.4. Stationary distributed sampling networks

Fig. 5 illustrates an example of a distributed network, NPL's Fugitive Emission Detection System (FEDS) for monitoring CH_4 [100]. An analyser is connected to a number of sampling inlets distributed around a site via tubes, ambient air is drawn through each inlet using a pump. Fig. 6 shows a heat map representing the concentration measured by the analyser at each sampling location. In this particular system the concentration measurements are combined with reverse dispersion modelling [101] of wind data to estimate emission rates.

FEDS has been deployed in a study to understand CH_4 emissions from Anaerobic Digester sites. The analyser is an optical spectrometer that is tuned to measure CH_4 concentration. This system consists of up to 15 independent sample inlets. Normally, the system is configured to sample at each tube inlet location over a period of approximately 4 min, 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 even if the tube length should be limited to around 300 m to minimise the response time.

A similar system [102] provides long-term continuous monitoring (detection, localisation and quantification) of CH_4 emissions at an oil and gas facility using a multi-open-path laser dispersion spectrometer combined with Bayesian analysis algorithms using Monte Carlo Markov Chain (MCMC) inference.

3.3.5. Stationary distributed low-cost sensors for area and site level quantification

Currently there are no validated methods based on sensors that can survey (detect and localise) emissions and quantify H_2 emissions over a large area and provide continuous time coverage. Techniques described in sections 3.3.1 and 3.3.4 have inherent limitations. First, tracer only provides a snapshot in time. Second, distributed sampling has limited spatial coverage due to the logistical challenges of deploying tubes across a site and provides near-continuous coverage.

There are sensor-based solutions being developed for CH_4 and/or air quality applications, for example those reported in Refs. [103–105]. The development of standards to test, select and deploy low-cost sensors (for air quality applications) is a rapidly developing area [106,107], while further studies are required to investigate the applicability of these systems and standards to H_2 monitoring.

3.4. Direct quantification of vented and ducted H_2 emissions and incomplete combustion

Direct quantification refers to a measurement obtained at a point in space in the vent, stack or exhaust, not a measurement at a point in space away from the source where the vented emission has diffused in air over a wider area. Quantification of diffused vented emissions are covered by techniques discussed in the previous section. We define two sub-categories as described in the following sub sections.

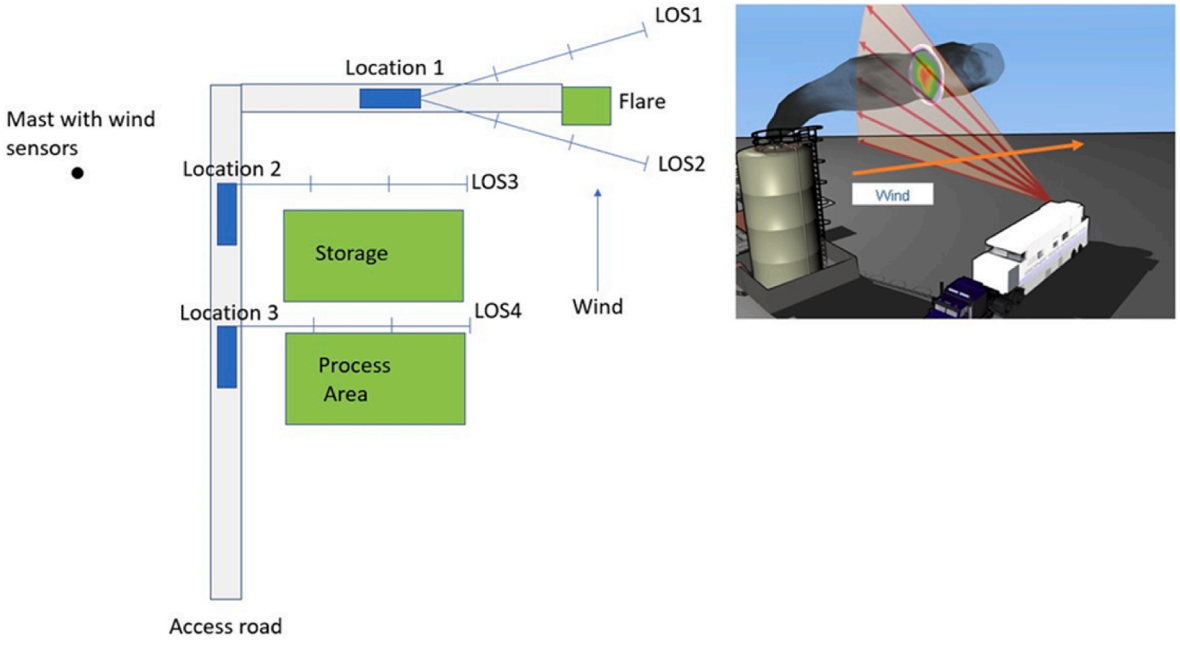

Fig. 4. Sketch of a concept optical system.

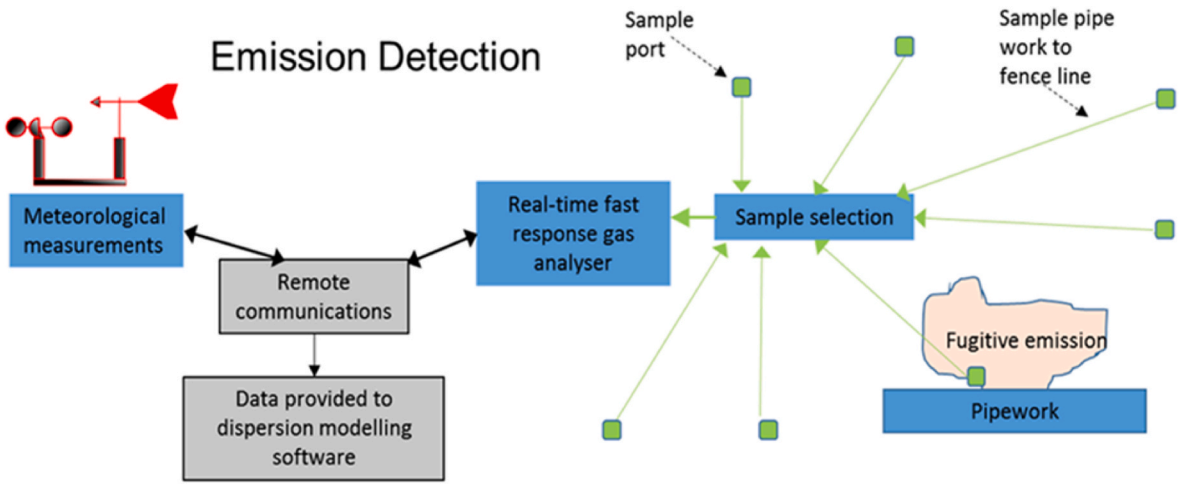

Fig. 5. Sketch of a distributed network for gas emissions monitoring.

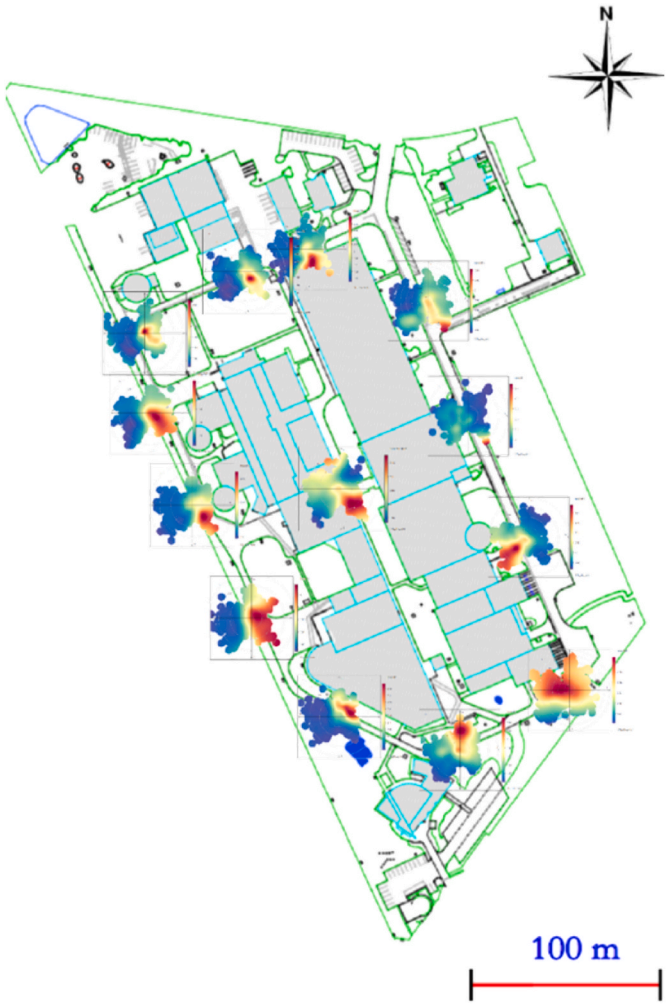

Fig. 6. Concentration map calculated by FEDS.

3.4.1. Direct quantification of vented emissions

This category assumes the quantification of pure H_2 where it is feasible and cost effective to install a flow meter. Estimation of vented emissions may involve direct measurements using mass or volumetric flow instruments. Examples that could provide a continuous measurement are: anemometers (vane or hotwire) or meters (turbine, Coriolis, orifice or thermal mass). There are two scenarios: continuous measurement using installed devices and 'snap-shot' measurement made at the end of the vent pipe. An example that could provide a snap-shot measurement is a calibrated vent bag. However, direct measurement of emissions related to process vents is challenging to perform, mainly resulting from the diversity of:

- Volume flow rate of the vented gas – variable flow rate depending on the type of discharge and operating conditions (diameter, pressure) requires determining the optimal measurement range before starting the measurement.
- Unpredictable duration of venting activity – in the case of process vents that are the result of failures or non-standard situations, proper measurement preparation and measurement are impossible and may pose an additional risk to safety.
- Geometry of the measurement site – in the case of devices inserted into the vent such as anemometers, the diameter of the device must be properly selected in relation to the vent line diameter.

Additional difficulties during snap-shot measurements of H_2 emissions from process vents may be due to access to vent columns, the ends of which are located high above the ground level, and the need to use measuring devices designed for operation in explosion hazard zones (e.g. ATEX).

For these reasons, engineering calculations are often used when estimating emissions associated with operational vents. These calculations require, at a minimum, a measurement of: gas pressure before and after the venting event, gas temperature, ambient temperature and physical volume of the vented equipment or system.

3.4.2. Direct quantification of ducted emissions and products of combustion

Ducted emissions cover a variety of scenarios:

- Open flares.
- Post combustion.
- Slip (the escape of unburnt H_2 via a vent or exhaust).
- Fugitive emissions that have been ducted from an enclosed space, for example. electrolyser, compressor and storage housings.

An unknown quantity in these scenarios is the gas matrix, for example emissions that have been created during a combustion process (commonly referred to as 'pollutants') such as NO, NO_2, and CO.

Mobile remote sensing-based Raman spectroscopy could be a contender for monitoring open flares as these objects and their surrounding area are normally inaccessible. The amount of unburnt H_2 will

depend on the flaring efficiency, this is assumed to be negligible [108] due to the high flammability of H_2 but the amount of emissions may depend on how the flare is used. In some cases it may not be cost effective or feasible to flare, therefore emissions may be released intentionally.

Continuous Emission Monitoring System (CEMS) also known as Automated Measuring System (AMS) whose spatiotemporal coverage area is at the bottom right of Fig. 1, are used for directly monitoring pollutants from sources of combustion (via vents and stacks). These can be extractive where an aliquot sample is delivered to an analyser or in-situ for example where a spectroscopic based technique is used to measure the absorption of light across a vent or stack to measure the concentration of a particular species or range of species. Existing standard methods (e.g., EN14181 [109] and EN15267 [110]), are currently used to monitor a wide range of pollutants, but do not include H_2 within their scope.

4. Future method development

4.1. The process for method development and the evolution of a method

To help ensure that new methods are adopted by industry and regulators, where possible their format and content should be based on existing methods that have similar scope in the NG sector. In addition, the criteria defined in section 2.1 should be used as a check list to ensure the method contains the essential elements to provide metrologically robust data (e.g., a clear definition of the physical magnitude to be measured, a sampling strategy and quality assurance procedures). Tables 4 and 5 define the criteria for the basic instrument specification and performance criteria respectively. In addition, the instrument should be suitable for conditions of use (e.g. intrinsically safe, portable etc).

Before the method and instrument undergo laboratory testing (under controlled conditions) a set of test facility requirements should be defined (for example: preparation of gas mixtures and ventilation requirements and to cover the principles set out in ISO 9001 [111] and ISO 17025 [112]).

Fig. 7 illustrates the evolution of a method following the method development process. The purpose of method validation is to demonstrate that the method meets the specification performance criteria described above and contains all the essential elements of a method. The validation should include laboratory testing, testing against a blind controlled release of a target set of gases, testing of the practical application of the method within representative scenarios (for example, at an electrolyser site), and a check of quality control and assurance procedures.

Following standardisation, formally developed by expert working groups within technical committees convened by the Comité Européen de Normalisation (CEN) which produces EN standards or International Organisation for Standardisation (ISO) which produces ISO standards or national standardisation bodies such as the British Standards Institute (BSI) or Deutsches Institut für Normung (DIN) in Germany. A method should routinely undergo verification to check that it complies with defined criteria and quality control procedures on a given day (for example, proving compliance with ISO17025). An example of a verification process is a Performance Test (PT) scheme [113]. 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 which provides a means for personnel, equipment and an organisation to demonstrate compliance with quality requirements [114].

Table 4
Basic instrument specification.

Criteria	Description
Selectivity to H_2 and interferences.	The selectivity will be important if the instrument is to measure the concentration of a mixture of gases (e.g., blended H_2 and CH_4) or where there is likely to be an interfering emissions source. For instruments that utilise non-selective sensors then the ratio between the actual concentration of the intended species to measured and the instrument readout (i.e., response factor) should be understood.
Range of concentration that can be measured	From the lower limit of the range (i.e. limit of detection) to the upper limit of the range. Note that high concentrations could have a temporary (i.e., hysteresis) or permanent (i.e., poisoning) effect on the sensor.
Ability to operate in Oxygen depleted environments (if applicable)	An understanding of the conditions in which the instrument is to be used is important.

Table 5
Instrument performance criteria.

Criteria	Description
Response time	From a change in the measurand to the corresponding change in the displayed output. This is a function of the response time of the sensor technology, the sampling technique (e.g. a sniffer that samples air via a length of tube, sampling rate, and flow rate) and instrument configuration (e.g. averaging).
Linearity	It is important to understand whether the instrument's response to a change in concentration is linear or non-linear over the concentration range that will be used and whether the output may saturate within that range and implement and validate an appropriate calibration method.
Uncertainty	Instrument accuracy and precision which will contribute to the uncertainty of the method. Also, determine whether the uncertainty is to be expressed as standard or expanded, if the latter determine the coverage factor.
The detection limit	Must be lower than the concentration threshold used to determine whether a leak has been detected.
Sensitivity to environmental factors	For example: humidity, temperature and wind.
Drift	This should be expressed over a defined period of time.

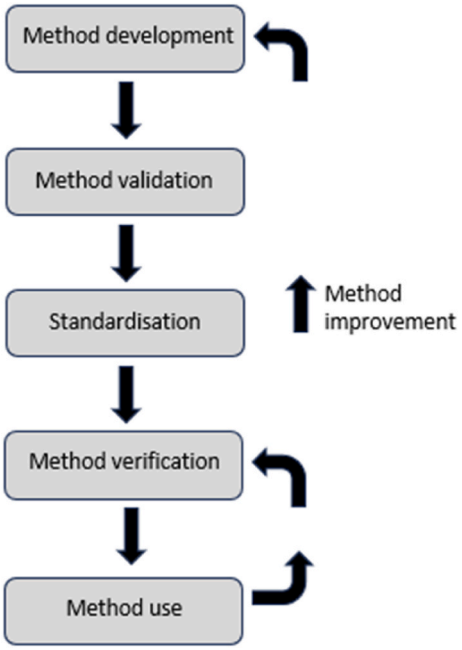

Fig. 7. The evolution of a method.

4.2. Discussion on method development – high TRL

The following describes how techniques would be developed into robust monitoring methods, covering those that would adapt existing methodology and utilise commercially available instruments.

4.2.1. Detection of H_2 leaks at component level

Since there are H_2 capable instruments on the market (TRL 9 or 10 – commercially available [115]), NG standards (e.g., EN15446) that could be adapted for H_2 and a recently published good a practice guide [116] on detecting leaks, then the adoption of methods to detect leaks at component level should be possible without the need for significant instrumentational development or development of a methodology from first principles. However, there will be challenges (aforementioned in section 2) specific to H_2 to overcome, such as the diffusion of H_2 in air will require a suitable sampling strategy to be designed (e.g., density of sampling locations in space, speed at which an instrument probe is passed over a component etc).

For the adoption of OGI further studies are required to investigate whether impurities (already present) in the H_2 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. OGI has been used as a complementary surveillance technique in NG (i.e., to remotely identify the presence of emissions over a wide area), it is conceivable that acoustic cameras could instead fulfil this role for H_2. Therefore, such a method could involve the complimentary use of sniffers (or passive instruments) and an acoustic camera.

Guidance on the selection of technology for a particular use-case and how complimentary sensor technologies could be integrated would be of benefit to enhancing the performance and scope of methods. Table 6 provides a basic comparison of instrument (sensor) technologies based on manufacturers data, and laboratory and field testing carried out by NPL [108]. The test data quoted is based on tests carried out with instruments, therefore they reflect the behaviour of the sensor and specific instrument design. These results provide a basic guide on choice of sensor technology for particular use cases, for example, metal oxide sensors could never be used to measure H_2 in Oxygen depleted environments, whereas a thermal conductivity sensor may be more suited. The table also indicates where additional measurements may be required (in addition to measuring H_2), for example metal oxide sensors may require a measurement of temperature and humidity to compensate for their sensitivity to these environmental factors, whereas an electrochemical sensor may be more suited.

4.2.2. Detection and quantification of H_2 leaks at component level

The detection and quantification of leaks at component level could be used to build (bottom-up) inventories of emissions. These bottom-up measurements could be extrapolated to estimate emissions at a larger spatial scale, for example a whole site. However, in the NG sector outlier emissions values can have a strong influence on average emissions [117]. Also, care should be taken to ensure that 'snap-shot' measurements are representative of emissions on a larger temporal scale, and the effect of a lack of data from inaccessible areas. An understanding of the uncertainty in the measurements provided by such methods are critical as well as the scope of what the measurements represent. In the NG sector 'bottom up' inventories can be reconciled with 'top down' measurements (i.e., at large area and site scale), but this can be challenging [117].

Concentration with sampling flow rate measurement (e.g., High Flow), bagging and correlation curves are used in the NG sector. Bagging is described in an EPA protocol and correlation curves in standard EN15446. Bagging has potential if the appropriate materials that are used to contain the H_2 sample can be identified and deployed and the necessary safety precautions taken. The performance of an H_2 concentration analyser or sniffer instrument would need to be considered too. Since correlation curves are based on the compilation of an existing library which as far as the authors are aware do not exist H_2, then development of a method based on correlation curves would require significant effort to compile a comprehensive library.

Development of a H_2 capable concentration with sampling flow rate measurement method will require an instrument that can measure H_2 concentration. In addition to defining the performance specification of the instrument, the performance of the flow meter would need to be considered too (i.e., range, linearity and uncertainty and effect of temperature). Since H_2 capable instruments (measuring concentration) are commercially available and that this is an established technique in the NG sector then the adoption of this technique for H_2 should be possible without the need for significant instrumentational development or development of a methodology from first principles. However, as with sniffer techniques there may be challenges specific to H_2 to overcome. Acoustic cameras may present specific challenges, for example, acoustic reflection from physical objects that could present false results, hence the need to test within a representative environment.

For component level detection and quantification, the next steps are to write draft methods, undertake laboratory and field tests (controlled

Table 6
Comparison of sensor (instrument) technologies.

Characteristic	Sensor technology				
	Catalytic	Metal Oxide Semiconductor	Thermal conductivity	Pd-alloy	Electrochemical
Data based on manufacturers data					
Selectivity to H_2	✘	✘	✘	✓	Depends on design
Maximum range	~ 50,000 ppm	N/A	1,000,000 ppm	50,000 to 1,000,000 ppm depending on instrument	NA
Ability to operate in O_2 depleted environments	✘	✘	✓	✓	✓
Response time (90 %)	Fast (<30s)	Fast (<30s)	Fast (<30s)	Fast (<30s)	Slower (minutes)
Sensitivity	High	High	Greater than ~ 4000 ppm	Highest	High
Data based on tests					
Linearity (tested between 4000 and 40,000 ppm)	Linear	Nonlinear	Nonlinear	Nonlinear above 100 ppm	Nonlinear
Cross interference to CH_4 (at 25,000 ppm)	Tests not conducted as these sensor technologies are not selective			0.5 ppm	NA
Insensitive to temperature and humidity	NA	✘	NA	✘	✓

NA Information not available.

release and representative environments) to evaluate the instrument and method performance, including a definition and test of a sampling strategy (e.g. sampling locations relative to the component of interest) that takes into consideration the properties of H_2. The pre-Normative Hydrogen Release Assessment (NHyRA) consortium [118] are currently developing such methods and validating them in the laboratory, against controlled release and at sites across the H_2 value chain. The results from these tests would then be used to refine the method.

4.2.3. Surveillance and quantification of H2 emissions at area and site level

Developing H_2 methods would require technical development for techniques such as tracer correlation and a H_2 capable FEDS (HFEDS), define instrument performance criteria, primarily to understand how the dispersion of H_2 determines the sampling strategy (location and density of sampling locations), identifying suitable tracer gases and assessing techniques to estimate emissions rates from concentration and wind measurements (such as reverse dispersion modelling). A first step could be the development of models to help determine specific sampling strategies based on the emissions source characteristics (e.g. size, predicted emissions rate etc) and their environment and how H_2 (or tracer) would be transported through the air. For each use case the relevant characteristics (e.g. density of sensor locations) of sampling strategies needs to be defined too, so that stakeholders (e.g. instrument providers and users) can agree on what the relevant parameters are for a given scenario. Such definitions could be based on an existing methane framework [43] which provides a framework for describing emission sources and sampling strategies, much of which is applicable to H_2. Steps following on from this work would be to develop these sampling strategies based on measurements against controlled releases and within representative environments.

4.2.4. Direct quantification of vented and ducted emissions and sources of combustion

Extending the scope of existing CEMS standards to include measurement of H_2 would require defining data measurement and quality objectives (e.g., emission limit values) and performance requirements for H_2 instruments. Also, 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 H_2, and method validations must also be performed to assess the method's performance, capabilities, and limitations.

An instrument to measure concentration may need to be specifically designed (depending on the design specification for the monitoring system) for the conditions that would exist within a combustion vent, i.e. temperature, up to pure H_2 concentrations due to slip (e.g., escape of unburnt H_2 during starts and stop events), water vapour, creation of gases due to the combustion process and impurities.

4.3. Discussion on method development – lower TRL

The aforementioned methods for the detection and quantification at component level are based on "walk over" survey techniques that only provide a snapshot measurement in time and not provide coverage of inaccessible areas. Methods are needed that include the continuous monitoring of H_2 and covering large areas (such as pipelines) by employing a network of sampling points. The US based National Energy Technology Laboratory [54] and EU based Optic Fibre-based Hydrogen Control Systems (OPTHYCS) [53] 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.

Distributed sampling (involving the sampling of ambient air to a central analyser via a series of tubes) involves the physical deployment of tubes across a site and use of high-cost analysers, this limits the spatial and temporal coverage and density of sampling. Sensors (which individually are a much lower cost compared to an analyser) could be deployed to increase the spatial and temporal coverage and density. However, sensors have lower performance (in particular, selectivity to H_2, cross interference to other species and sensitivity) compared to a mass spectrometer based analyser [108].

A recommended area of research is to investigate the deployment of sensors (permanently installed and/or drone based) to extend the spatial and temporal coverage of a distributed sampling system. It is envisaged that the analyser within the distributed sampling system is calibrated to a reference standard and then the sensor outputs are periodically corrected relative to the analyser. This methodology has been investigated for the quantification of CH_4 using metal oxide semiconductor sensors [119], the same sensor types are sensitive to H_2.

The development of a Raman based LIDAR system could conceivably provide similar capabilities to DIAL [120] depending on its performance. DIAL can provide spatially resolved data over large areas, track plumes, provide coverage of inaccessible areas and provide a reference for 'top-down' verification of 'bottom-up' measurements. Further work is required to develop this technique beyond an experimental proof of concept (TRL 3). DIAL is part of standard method EN17628 [40], therefore, it is conceivable that such as method could be based on similar methodology, quality control and assurance and the performance requirements within the standard would provide an aim for future development.

It is envisaged that a range of complimentary methods will need to be deployed to cover the spatial and temporal scales of H_2 monitoring, the data from each will need to be consolidated. Actions to reduce emissions will require data from multiple methods or data sources. Therefore, it will become increasingly important for the data output from methods to be standardised, i.e. for data to be expressed in a common format and structure. This could be a simplistic as insisting on SI units to report data; in some cases there will be need to flag scenarios where this is not possible, for example comparing data from different time periods which can't be reliably extrapolated. For each method there needs to be a traceable reference that methods are validated against and periodically verified against.

A challenge is the rapidly increasing emergence of AI to manage, process and analyse data. Reliable data is underpinned by the metrology. The European Metrology Network for Mathematics and Statistics is a focal point for best practice in mathematics and statistics in metrology covering themes such as AI [121]. Adhering to metrological principles such as traceability, transparency and repeatability will be vital to ensure that emissions reduction strategies are based on reliable data.

5. Conclusions

Methods based on acoustic cameras and sniffers for detecting H_2 and concentration measurement combined with sampling flow rate and bagging for quantifying H_2 emissions at component level are widely used in the NG sector and (in our opinion) are most likely to be adapted for H_2 in the near future. The challenge will be understanding how to adapt their use under different scenarios (e.g., developing and tailoring sampling strategies for different leakage scenarios) and understanding their performance under "real word" conditions.

Methods and their associated instruments for monitoring of H_2 emissions at area and site level such as HFEDS and Tracer are widely used in the NG sector, but there are technical challenges to overcome (e.g. to understand the transport of H_2 in the atmosphere). In particular, Raman is still at an early stage in research and development. Despite the challenges the reward would be the ability to estimate diffused emissions from multiple fugitive and vented emissions sources, inaccessible sources, this may facilitate the verification of bottom-up inventories. A Raman system, if based on DIAL (spatially resolved measurements) could have the potential to provide a rich data set in addition to quantifying emissions, such as 2D or 3D plume mapping and tracking over a wide area and ability to monitor challenging in accessible such as flares.

Standards exist for Continuous Emissions Monitoring systems that are used for the monitoring of pollutants which could be adapted to include H_2 for monitoring sources of combustion. Work is required to determine an instrument specification and literature search to identify availability of commercially available instruments that could be used for this purpose.

The primary drivers for H_2 monitoring are to protect the environment, optimise the efficiency through the value chain and provide a safe, resilient and secure energy carrier. This can be achieved by minimising leaks, tracking emissions using inventories and optimising operations throughout the value chain. There needs to be a clear means of specifying methods based on monitoring aims and drivers and a robust means of integrating data from complimentary methods and data at different scales to enable the appropriate actions to be taken. Robust methods that provide trustworthy data (underpinned by metrological principles) are an essential part of the information and data need to make informed decisions. The environmental benefits are that the appropriate and cost-effective strategies can be implemented to reduce emissions (e.g. fix leaks) and also an emissions inventory based on validated methods will better serve an understanding of how the H_2 economy will impact climate.

CRediT authorship contribution statement

Andy Connor: Writing – review & editing, Writing – original draft. **Haydn Barros:** Writing – original draft. **Rod Robinson:** Writing – review & editing. **Alessandro Guzzini:** Writing – review & editing, Writing – original draft. **Marco Pellegrini:** Writing – original draft. **Cesare Saccani:** Writing – original draft. **Jadwiga Holewa-Rataj:** Writing – review & editing, Writing – original draft. **Tomasz Kuchta:** Writing – review & editing, Writing – original draft. **Henning Wigger:** Writing – review & editing, Writing – original draft. **Thomas Vogt:** Writing – review & editing, Writing – original draft. **Violeta Bescos Roy:** Writing – review & editing. **Victoria Krohl:** Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.meaene.2025.100069.

Data availability

No primary research results, software or code have been included as part of this review. Definitions referred to in this article have been included as part of the supplementary material.

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