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Safe hydrogen injection management at network-wide level: towards European gas sector transition

Shimmer

Safe Hydrogen Injection Modelling and Management for European gas network Resilience

D3.4. List of methods for gas leakage monitoring along with their physicochemical basis and scope of application and popularity

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ABSTRACT
This deliverable describes gas leakage monitoring and detection methods for gas networks which are currently used or planned to be used by gas network operators as well as emission measurement methods for gas networks. There are many methods available for both gas leak detection and emission measurement for gas networks which can be used for gas networks transporting natural gas and hydrogen mixtures. It is impossible to choose one optimal method because each method described in this document has its advantages and disadvantages. The choice of the optimal method for leak detection or emission measurement depends on the measurement conditions.

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List of Abbreviations

Table 0-1: List of abbreviations

Term	Explanation
NPW	negative pressure wave
RTTM	real-time transient model methods
PPA	pressure point analysis
MOS	metal oxide semiconductor
NDIR	non-dispersive infrared gas sensors
FID	flame ionization detector
LOD	low limit of detection
TCD	thermal conductivity detector
LEL	lower explosive limit
OGI	optical gas imaging
LDAR	leak detection and repair
GWP	global worming potential
AGI	acoustic gas imaging
SPL	sound pressure level
dB	decibel

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Executive Summary

The European Union has set ambitious goals for reducing CO_2 emissions over the coming decades and the crowning achievement of this effort is to be CO_2 neutrality in 2050. Hydrogen is to play an important role in this process. Hydrogen transport technologies in pressurized tanks are already well developed but hydrogen transport via the existing gas network is still the subject of many studies and tests. In order to ensure the safety of transport of the natural gas-hydrogen mixture gas leakage monitoring and detection from gas networks as well as methane emission measurement are very important. This report is a review of gas leakage monitoring and detection methods from gas networks and emission measurement methods.

There are many methods for detecting gas leaks from gas networks. The methods described in this report have been divided into 5 categories, i.e. sniffers, computational leak detection methods, Optical Gas Imaging (OGI), acoustic methods and laser methods. Sniffers are typically battery operated and handheld portable systems that may be used to detect gas leaks. The qualitative and quantitative measurement range of sniffers depends mainly on the type of sensor used. These devices can be equipped with methane or hydrogen sensors, or both sensors which can operate simultaneously or sequentially. Each of these devices can be used to detect leaks in gas networks transporting NG-H2 mixtures but will be characterized by a different leak detection limit depending on the composition of the NG-H2 mixture. Computational leak detection methods is a group of methods for detecting leaks located on gas pipelines which is based on mass balance. This group of methods includes basic mass balance methods (in which the amount of gas entering and leaving a given section of the network is compared), real-time transient model methods (RTTM) (which enable dynamic compensation of flow changes), negative pressure wave (NPW) (provides information on the leak flow rate and leak area), pressure point analysis (PPA) (in this method the results of pressure measurements along the monitored gas pipeline are compared) and statistical methods (which use mathematical models that first require calibration on the actual network). The OGI technique can only detect leaks that emit infrared-active gases. Therefore, it cannot be used directly to detect leaks in gas networks transporting pure hydrogen. However, it could be used in the case of detecting leaks in gas networks transporting NG-H2 mixtures, where methane will be a tracer allowing the use of the OGI technique. Acoustic methods can detect and locate gas leaks even from small cracks or perforations in gas networks but are not currently used by the TSO and DSO operators involved in the SHIMMER project. To detect methane emissions two types of lasers are used: LIDAR and diode lasers, based on the absorption of IR radiation by methane molecules. Similar as in the case OGI technique these methods could be used in the case of gas networks transporting mixtures of hydrogen and natural gas, but their sensitivity will be lower than sensitivity for natural gas. Laser leak detection techniques in hydrogen networks should be classified as low TRL techniques for which there are no commercial solutions on the market. It should be added that most of the methods used to detect leaks can be used with the same effect for networks transporting natural gas and networks transporting NG-H2 mixtures.

Various measurement methods are used to quantify methane emissions from gas networks. These methods can be used, with certain limitations, to quantify methane and hydrogen emissions when transporting mixtures of natural gas and hydrogen or pure hydrogen. A correlation method was described in the standard EN 15446:2008 but due to the different physico-chemical properties of methane and hydrogen it should not be used for emission measurement of hydrogen and natural gas-hydrogen mixtures until dedicated correlation equations for hydrogen are developed. In the case of natural gas-hydrogen mixtures, it is possible to measure methane emissions also with dedicated devices for the airflow method and then estimate the hydrogen emission level based on the composition of the mixture. Similar as in the case of leakage detection, computational methods are used for measuring methane emissions from gas pipelines. These methods are (1) the method of measuring the pressure drop in an isolated section of a gas pipeline, (2) direct measurement method, which requires maintaining constant gas pressure in a section of the leaking gas pipeline isolated from the rest of the network and (3) the pressure variation method, which uses the principle that the rate of gas flow at the leak site is proportional to the gas pressure prevailing in the network. Bagging methods could be used for measuring the emission of pure hydrogen and its mixtures with natural gas as long as measuring devices (gas meter, rotameter) appropriate for the given type of gas are used. In the case of using OGI techniques for quantitative emission measurement, an increase in the hydrogen content in the NG-H2 mixture will result in an increase in

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the detection limit and quantification limit. The last method that can be used for pure hydrogen, methane as well as their mixtures emission measurement is the acoustic method. If the acoustic method is used to measure emissions from gas networks transporting the NG-H2 mixture, the measurement result will be the sum of the emissions of both components of the mixture. Summarizing, most of the methane emission measurement methods used by TSO and DSO operators will still be able to be used for NG-H2 mixtures.

The report also assessed methods for detecting leaks and measuring hydrogen emissions taking into account (1) type of detected/measured gas, (2) resistance to changes in gas composition, (3) availability of measuring devices, (4) cost of purchasing and maintaining the equipment, (5) scope of application, (6) staff qualifications and (7) other advantages and disadvantages. Each aspect was assessed on a five-point scale of 1-5. The ranking of methods was performed separately for the emission detection and measurement method. It is not possible to indicate a universal method for detecting leaks as well as for measuring and estimating emissions from gas networks transporting NG-H2 mixtures. Each of the methods considered has advantages and disadvantages, as well as the optimal area of application of a given method. The choice of the appropriate method depends on the measurement conditions.

About the project: The European natural gas infrastructure provides the opportunity to accept hydrogen (H_2), as a measure to integrate low-carbon gases while leveraging the existing gas network and contributing to decarbonisation. However, there are technical and regulatory gaps that should be closed, adaptations and investments to be made to ensure that multi-gas networks across Europe will be able to operate in a reliable and safe way while providing a highly controllable gas quality and required energy demand. Aspects such as material integrity of pipelines and components, as well as the lack of harmonisation of gas quality requirements at European level must be addressed in order to facilitate the injection of H_2 in the natural gas network.

In this context, the SHIMMER project (Safe Hydrogen Injection Modelling and Management for European gas network Resilience) was selected for funding as part of the 2023 Clean Hydrogen Partnership programme. SHIMMER aims to enable a higher integration of low-carbon gases and safer H_2 injection management in multi-gas networks by strengthening the knowledge base and improving the understanding of risks and opportunities in H_2 projects.

It will do this by:

- Mapping and assessing European gas T&D infrastructure in relation to materials, components, technology, and their readiness for hydrogen blends.
- Defining methods, tools and technologies for multi-gas network management and quality tracking, including simulation, prediction, and safe management of network operation in view of widespread hydrogen injection in a European-wide context.
- Proposing best practice guidelines for handling the safety of hydrogen in the natural gas infrastructure and managing the risks.

1 Introduction

1.1 Purpose of the document

The introduction of hydrogen into the existing gas network will require network operators, both distribution and transmission, to adapt their leak detection and monitoring methods, as well as emission measurement methods to the type of transported medium. Therefore, the results of gas leakage monitoring and detection methods for gas networks and emission measurement methods, and their assessment described in this report are very important for ensuring the safety of use of gas networks transporting natural gas-hydrogen mixtures. These results are therefore important from the point of view of achieving the project objectives.

1.2 Intended readership

The results presented in this report are important for gas network operators, both distribution and transmission. TSO and DSO operators are responsible for ensuring the safety of gas network operation. From this point of view, knowledge of methods for monitoring and detecting gas leaks is important. Considering gas losses and network balancing, it is important to have knowledge of emission measurement methods.

1.3 Structure of this document

This document is divided into three main parts. The first part describes leak detection methods. The second part describes quantification/measurement of emission methods, including methods used to measure hydrogen emissions. The last part evaluates the methods described in the report in terms of selecting the most optimal one, both for gas leaks and emission measurements.

1.4 Stakeholder involvement

The list of devices (sniffers) prepared by INiG that can be used to detect leaks of natural gas-hydrogen mixtures was made available to TSO and DSO operators involved in the project in order to supplement it with devices that the operators currently use or would like to use in the future. Also the descriptions of leak detection and emission measurement methods using mass balance were consulted with the experience of TSO and DSO. Report containing technical descriptions of leak detection and emission measurement methods was made available for consultation to other partners participating in the project.

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2 Leak detection methods

There are many methods for detecting leaks in gas networks. This chapter focuses on the applicability of methods currently used or planned to be used by gas network operators and their partners. The survey conducted among the consortium partners shows that:

- 5 of the 7 partners use sniffers,
- 3 of the 7 partners use diode lasers,
- 2 of the 7 partners use mass balance methods it this RTTM method,
- 2 of the 7 partners use optical imaging methods and another 4 plan to introduce optical methods in the future
- none of the 7 partners use the laser (LIDAR) methods, but three of them are considering using this method in the future,
- none of the 7 partners use the acoustic method, but one of them is considering using this method in the future,
- none of the 7 partners use the tracers methods and none of them are considering introducing it in the future.

2.1 Sniffers

Sniffers are typically battery operated and handheld portable systems that may be used to detect leaks. Devices belonging to this group include both single-gas detection devices and multi-gas devices. The qualitative and quantitative measurement range of sniffers depends mainly on the type of sensor used.

2.1.1 Type of sensors

2.1.1.1 Metal-Oxide-Semiconductor (MOS) sensors

These sensors work using a reversible process of gas adsorption on the surface of a heated metal oxide. Absorption of the analysed gas on the surface of the oxide, followed by its catalytic oxidation, results in a change in the electrical resistance of the oxide material, which is proportional to the concentration of the analysed gas in the mixture. [1] There are two types of sensors available on the market. [1; 2]

- N-type sensors, in which there is a change in the resistance of the receptor element when the presence of gases is reduced. The mechanism of operation of these sensors is based on the phenomenon of chemisorption of oxygen contained in the air on the oxide layer, which blocks the flow of electrons. The consequence of this is an increase in the resistance of the sensitive sensor layer, which decreases when reducing gas molecules appear in the mixture, which, reacting with bound oxygen, leads to the release of electrons
- P-type sensors, in which there is a change in the resistance of the receptor element when oxidizing gases are present. These types of sensors work by the opposite principle of n-type sensors; in p-type sensors, molecules of gaseous compounds remove electrons from chemically sensitive metal oxide layers, thereby creating charge carriers and causing a drop in resistance.

Solid-state sensors can be used to detect and measure, among other things, the concentration of hydrogen and hydrocarbons, including methane [1].

2.1.1.2 Pellistors/ Catalytic sensors

Catalytic sensors (pellistors) are used to detect combustible gases. A catalytic sensor consists of two platinum coils active and inactive. The first is activated with a catalyst made of metal (platinum or palladium), while the

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second inactive one without a catalyst acts as a reference element. The presence of a flammable compound in the gas is detected by monitoring changes in resistance resulting from an increase in temperature. The temperature increase is the result of catalytic oxidation of combustible compounds. This increases the resistance of the active coil and causes a voltage imbalance on the Wheatstone bridge [1, 3, 4]. Despite the use of a bridging circuit that largely compensates for the influence of the environment, these sensors remain sensitive to external factors, especially those that affect thermal parameters such as gas flow velocity [5].

The lack of pellistor selectivity is associated with potential interference effects from other flammable gases such as hydrogen. Therefore, sniffers equipped with pellistor sensors should not be used to detect leaks on gas networks transporting NG-H2 mixtures.

2.1.1.3 Electrochemical sensors

Electrochemical sensors measure the concentration of a target gas using its oxidation or reduction reaction at the electrode, depending on the type of gas, e.g. carbon monoxide can be oxidized to carbon dioxide and oxygen reduced to water. The oxidation reaction causes electrons to flow from the sensing electrode to the counter-electrode through an external circuit, while in the case of reduction the flow of electrons is reversed. The result is a current proportional to the concentration of the test gas in the mixture [3]. For the most part, electrochemical sensors are sensitive, selective, inexpensive and can be widely used for leak detection, emissions monitoring and fire safety [6]. Electrochemical sensors can be used to detect leaks of both gases methane and hydrogen.

2.1.1.4 Non-dispersive infrared gas sensors (NDIR)

Non-dispersive infrared gas sensing (NDIR) is a unique optical sensing technique where IR radiation interacts with the targeted analyte and in the process, it is absorbed. This absorption is unique for every gas and hence, based on the absorption characteristics, gas molecules can be fingerprinted and distinctively identified [7]. These measuring gases are divided into atmospheric pollutants (such as SOx and NOx), flammable and explosive gases (e.g. CH4, C2H2) and toxic gases (e.g. CO, NH3) [8]. NDIR sensors are not affected by typical catalyst poisons like silicone and sulfur [8]. Unfortunately, NDIR sensors cannot be used to detect molecules that are inactive in infrared. This type of molecule is, among others, hydrogen. For this reason, sniffers equipped with NDIR sensors will have limited use only for NG or NG-H2 mixtures.

2.1.1.5 Flame Ionization Detector (FID)

FID sensors are relatively rarely used in sniffers. This is due to the fact that this type of sensors cannot be used in devices intended for use in explosion hazard zones. The advantages of sniffers equipped with FID sensors are: low limits of detection (LOD) and wide linearity range. However, due to the principle of operation of these sensors, they can only be used to detect organic compounds containing carbon. Therefore, similarly to NDIR sensors, they can be used to detect leaks only in gas networks transporting NG or NG-H2 mixtures.

2.1.1.6 Thermal conductivity detector (TDC)

Micro TCD sensors (mTCD) are most often used in sniffers due to their smaller size and greater sensitivity than typical TCD sensors. TCD is truly a universal sensor and can detect air, hydrogen, hydrocarbons and many other compounds [9]. The measurement principle using TCD sensors is based on differences in the thermal conductivity of individual gases. For this reason, the TCD is a non-specific sensor. The non-selectivity of the TDC is associated with potential interference effects from methane and hydrogen. For this reason, sniffers equipped with TCD sensors should not be used to detect leaks in gas networks transporting NG-H2 mixtures.

Table 2-2 summarizes the literature review regarding sensors used in sniffers.

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Table 2-1: Type of sensors – summary

Sensor type	Methane	Hydrogen	NG-H2 mixtures
Metal-Oxide-Semiconductor	Yes	Yes	Yes
Catalytic	Yes	Yes	No
Electrochemical	Yes	Yes	Yes
Non-dispersive infrared	Yes	No	Yes
Flame Ionization	Yes	No	Yes
Thermal conductivity	Yes	Yes	No

Due to the lack of selectivity, catalytic and TCD sensors cannot be used to detect leaks in gas networks transporting NG-H2 mixtures, as the readings of these sensors may be incorrect in the presence of both gases.

2.1.2 Sniffers - market review

The market review of available sniffers showed that there are devices equipped with methane sensors, hydrogen sensors, and both types of sensors (Appendix A).

2.1.2.1 Sniffers only for methane or hydrogen

The main group of sniffers are devices dedicated to detecting single gas leaks. Sniffers designed to detect methane are mainly equipped with semiconductor sensors. The other types of sensors used in these devices are sensors: non-dispersive infrared gas sensors, pellistors, flame ionization detector or thermal conductivity detector. Sniffers equipped with semiconductor sensors are very sensitive devices with a measurement range from several ppm to 1% v/v. However, sniffers equipped with catalytic sensors are designed to measure higher methane contents in the air, ranging from 1% to 100% v/v. Sniffers equipped with NDIR detectors have the widest measurement range. For this type of devices, the measurement range can be as much as 1 ppm to 100% v/v. Sometimes the measurement range of devices is given in relation to the lower explosion limit of methane, in the case of this type of devices the measurement range is most often up to 100% LEL. Sniffers designed to detect hydrogen include devices equipped with three types of detectors: electrochemical, semiconductor and catalytic. All sniffers of this type are characterized by high sensitivity allowing the detection of hydrogen in the air with a concentration of 0.2 to 1.0 ppm. In most cases, the upper measurement range is up to several %, which is related to the low lower explosion limit of hydrogen, which is 4%.

The group of devices enabling measurement of only one gas also includes sniffers in which the same measuring device can be equipped (at the configuration stage) with a methane or hydrogen sensor. In this case, two separate devices are required to measure the methane and hydrogen content in the air at the leak location. The advantage of this solution is that the operation of both devices is identical. Devices belonging to this group are equipped with catalytic, TCD or semiconductometric sensors. However, sniffers equipped with catalytic sensors are calibrated using one specific flammable gas, therefore their use for detecting flammable gas mixtures is limited

2.1.2.2 Sniffers for both gases, methane and hydrogen

These types of devices are equipped with hydrogen and methane sensors and can measure the concentration of both gases sequentially or simultaneously. Sequential measurement can be performed with a Cosmos device equipped with two semiconductometric sensors. This device allows you to detect a leak causing methane or hydrogen leakage at a level of 0.0000003 l/min. Alter, Drage and Honeywell devices allow simultaneous

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measurement of both gases. In this case, an electrochemical sensor is responsible for hydrogen detection. Methane is detected by a catalytic sensor (Alter) or NDIR (Drage and Honeywell).

2.1.3 Sniffers - method of measurement

Taking into account the results of the market review of available sniffers, it can be concluded that:

- sniffers with a methane sensor **– Approach 1,**
- sniffers with a hydrogen sensor **– Approach 2** and
- sniffers enabling simultaneous measurement of both gases**– Approach 3**.

can be used to detect leaks in gas networks transporting NG-H2 mixtures. Each of these three approaches will be characterized by a different leak detection limit depending on the composition of the NG-H2 mixture. In order to estimate the detection limits of individual approaches, calculations were made for 6 sample compositions of gas mixtures (Table 2-3).

Table 2-2: Composition of gas mixtures used in the calculations

Symbol	hydrogen content [% v/v]	methane content [% v/v]
H2_0	0	100
H2_5	5	95
H2_10	10	90
H2_20	20	80
H2_30	30	70
H2_100	100	0

Assuming that devices with a measurement range of 5-10 ppm allow the detection of leaks characterized by the leakage of the measured gas at the level of 0.1 l/min (0.14 m^3/day), Table 2-4 shows the estimated size of the leak that can be detected with each of the 3 presented approaches.

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Table 2-3: Size of detected leaks - three approaches

Symbol	Approach 1 (methane sensor)	Approach 2 (hydrogen sensor)	Approach 3		
			Methane sensor	Hydrogen sensor	Whole approach
H2_0	0.10 l/min	no detection	0.10 l/min	no detection	**0.10 l/min**
H2_5	0.11 l/min	2.00 l/min	0.11 l/min	2.00 l/min	**0.11 l/min**
H2_10	0.11 l/min	1.00 l/min	0.11 l/min	1.00 l/min	**0.11 l/min**
H2_20	0.13 l/min	0.50 l/min	0.12 l/min	0.50 l/min	**0.12 l/min**
H2_30	0.14 l/min	0.30 l/min	0.14 l/min	0.30 l/min	**0.14 l/min**
H2_100	no detection	0.10 l/min	no detection	0.10 l/min	**0.10 l/min**

The calculations presented in Table 2-4 show that in the case of NG-H2 mixtures in which the hydrogen content does not exceed 10%, sniffers equipped with methane sensors can be used to detect leaks without a significant loss in the sensitivity of the method. This means that TSO and DSO operators can use the sniffers currently in their equipment to leak control gas networks transporting this type of NG-H2 mixtures. In the case of mixtures with a higher hydrogen content (20-30%), the use of sniffers with methane sensors reduces the sensitivity of the leak detection method by approximately 30-40%. In this case, the use of sniffers equipped with a hydrogen sensor or both sensors does not improve the sensitivity of the method. This is due to the fact that with the same measurement range of both sensors, the gas sensor with the higher concentration in the mixture will react first. To be able to detect leaks at a level of 0.1 l/min for NG-H2 mixtures with hydrogen content (20-30%) requires the use of:

- methane sensor with a measurement range from 3-4 ppm or
- hydrogen sensor with a measurement range from 1-2 ppm.

The presented calculations show that sniffers equipped with methane sensors should be used to detect leaks in gas networks transporting NG-H2 mixtures whose main component is methane.

The presented calculations do not take into account possible interference effects that may occur during measurements in facility conditions. For this reason, as part of the implementation of task 3.3.2, leak detection tests were planned using sniffers:

- only for methane,
- only for hydrogen,
- simultaneous measurement of both gases.

2.2 Computational leak detection methods

Another group of methods for detecting leaks located on gas pipelines are methods that use input data such as gas flow, pressure, temperature, and appropriate computational algorithms to detect leaks [10, 11].

2.2.1 Basic mass balance methods

The most **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 [10, 11, 12]. A discrepancy between the amount of gas entering the system and the amount measured at the exit can indicate the presence of a pipeline leak. The accuracy of this method depends on the accuracy of the measuring instruments. In addition, this method gives much better results for time-fixed gas flows. If gas reception at exit points varies over time, this can lead to false alarms or increase leak detection time [10, 11, 12]. The correct functioning of this method is mainly based on the use of appropriate threshold values indicating the presence of leaks. An important disadvantage of this method is that it does not allow to directly indicate the location of the leak, but only to indicate the section of the gas pipeline where the leak occurred. The use of the probabilistic method in this area makes it possible to determine (based on a probability distribution) the regions where the leak occurs. The probabilistic method also makes it possible to analyse a series of scenarios describing possible events and types of leaks, in such a way as to assign each of them an appropriate probability, which can be updated using the input data [13].

Basic methods based on mass or volume balance are insensitive to changes in the gas composition in the pipeline, including hydrogen content, as long as the measurement devices used to measure the input and output streams are insensitive to such changes.

2.2.2 Real-time transient model methods (RTTM)

An improvement on the mass flow rate or volume balance-based method are methods referred to as RTTM, or **real-time transient model methods**. This method, unlike methods based on mass flow rate or volume balance, allows compensation for dynamic changes occurring in the pipeline. [10, 11]. The real-time transient model detects the abnormalities in the flowing fluid or gas using mathematical simulations governed by the fundamental physical laws such as conservation of mass, conservation of momentum, and conservation of energy. The pipeline operational parameters such as flow, pressure, and temperature are acquired by the Supervisory Control and Data Acquisition (SCADA) system in real-time, and the characteristic changes in these parameters are then used to detect, locate, and quantify the leakage in the pipeline. The discrepancies observed in the measured and calculated values will be flagged as an event of interest (leak here) when it exceeds a certain threshold [14]. If the calculated values are subtracted from the measured values, we get the values of the so-called residuals:

- X - the flow measured at the inlet minus the flow calculated at the inlet, and
- Y - the flow measured at the outlet minus the flow calculated at the outlet.

In a situation where the pipeline is airtight, then both the X and Y values should be close to zero. In contrast, when there is a leak, the X value will be greater than zero, while the Y value will be less than zero. These differences are much easier to identify than those used in the method based on mass flow rate or volume balance, so this method allows smaller leaks to be detected and generates fewer false alarms. The disadvantages of this method are: high computing power required, difficulty in calibrating mathematical models, long time in case of detecting small leaks [14].

Significant changes in the gas composition that affect its physicochemical parameters, e.g. density, require recalibration of the mathematical model used in the RTTM method.

2.2.3 Negative pressure wave (NPW)

Negative pressure wave is a popular method to detect the occurrence and location of leak incidents in oil/gas pipeline [15]. The negative pressure wave propagation method is a technique to locate leakages and defects in pipelines. The amplitude of negative pressure waves can be exploited to obtain information about the leak flow rate and leak area. A sudden change in density at the location of the leak causes a drop in pressure, generating a negative pressure wave that propagates both up- and downstream, where they are being detected by a pressure sensor. A time-of-flight analysis reveals the origin of the pressure wave and thus the leak location. [16]. The leakage location is usually determined by measuring the times needed for the negative pressure wave to arrive at the locations of pressure sensors located in upstream and downstream using equation (2-1; 2-2 and 2-3) [12].

$$l = \frac{u_{s-u}}{u_s}\left[\frac{L}{2} - \frac{t_2 - t_1}{2}(u_s + u)\right] \quad (2\text{-}1)$$

$$t_1 - t = \frac{l}{u_s - u}$$	(2-2)
$$t_2 - t = \frac{L - l}{u_s + u}$$	(2-3)

where:

- t is the time at which the leakage starts (s),
- t_1 is the time when the negative pressure wave arrives at the location of the upstream sensor (s),
- t_2 is the time when the negative pressure wave arrives at the location of the downstream sensor (s),
- L is the distance between the upstream and downstream sensor locations (m),
- l is the distance between the leakage location and the location of the upstream sensor (m),
- u_s is the velocity of sound in the fluid (m/s),
- u is the velocity of the fluid inside the pipe (m/s).

The principle of operation of the NPW method is shown in the fig. 2-1.

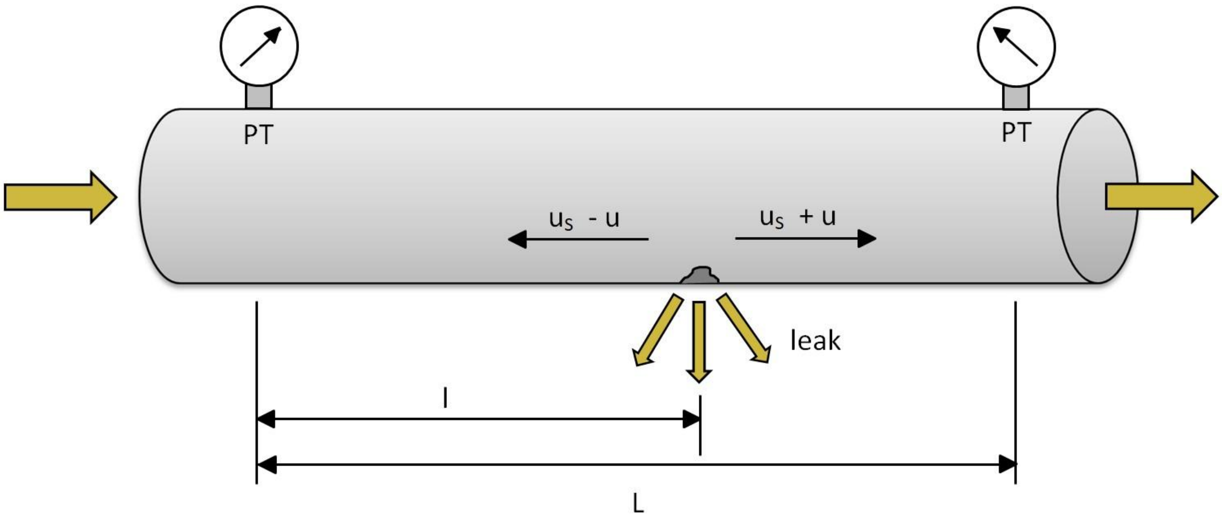

Figure 2-1: Schematic showing how a NPW-based leakage detection and localization method work (based on [12]

The advantage of the NPW method is the ability to detect leaks in real time with satisfactory precision, but the disadvantage is sensitivity to environmental noise.

Changing the composition of a gas by introducing hydrogen into it affects the velocity of sound. For this reason, in calculations carried out using the NPW method, it is necessary to take into account the current velocity of sound for a given gas mixture.

2.2.4 Pressure point analysis (PPA)

Another calculation method is one based on point pressure analysis. This method is based on the assumption that if there is a leak on a pipeline, the gas pressure in the pipeline decreases [10, 11]. This method requires continuous pressure measurements at various points along the gas pipeline [12, 17]. Pressure sensors can be spaced far apart from each other unless the location of the gas pipeline forces a denser distribution of the sensors. This is the case when the pipeline traverses steep hills, in which case pressure sensors should be placed at the highest points of the pipeline [10, 11]. To detect a leak in the gas pipeline, a comparison of the received results of gas pressure measurements in the pipeline with the average value is used. If the result of the

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measurement is lower to the average value by a certain threshold value, then it should be considered that the section of the gas pipeline under study is leaking [10, 11, 12]. However, this method has numerous disadvantages. One of them is that it does not give reliable results for gas flows that are unsteady over time. In addition, noise generated, for example, by the operation of valves, can both mask existing leaks and mimic leaks during normal pipeline operation. The size of the leak that can be detected by this method largely depends on the volume of the gas pipeline the larger the volume of the pipeline, the larger the leaks that can be detected by this method [10, 11].

2.2.5 Statistical methods

The last group of computational methods are statistical methods [10, 11, 12]. Statistical analysis is the simplest way to detect gas pipeline leaks without using a mathematical model. In this method, analysis of parameters measured at multiple locations along the pipeline, such as pressure and gas flow, is conducted. An alarm suggesting the presence of a leak is generated only when the measured values deviate in a statistically significant way from the assumed values. In order to correctly determine leakage thresholds at the system tuning stage, the variation of parameters in different states of pipeline operation in the absence of leaks is analyzed. Proper execution of the tuning process flows out the accuracy of the method and allows to effectively eliminate false alarms. If there is a leak in the system at the stage of tuning, it will be treated as a normal operation of the system, and therefore leaks of this size will not be detected using the method tuned in this way. This method is easy to use, reliable and easily adaptable to different pipeline configurations, but it does not provide an estimate of the size of the leakage [10, 11].

As in other methods using computational algorithms, in the statistical method it is necessary to adapt the algorithms to the changing physicochemical parameters of the gas.

2.3 Optical Gas Imaging (OGI)

Optical gas imaging is a popular leak detection technique, e.g. as part of LDAR procedures. The popularity of OGI techniques results from the savings in inspection time compared to the use of sniffers, and also the ability to perform inspections from a distance, which makes it easier to inspect hard-to-reach places. An OGI camera uses infrared radiation to detect gases. This technique can only detect leaks that emit infrared-active gases. Hydrogen, unlike methane, is not an infrared-active gas, therefore the OGI technique cannot be used directly to detect leaks in gas networks transporting pure hydrogen.

Great interest in the possibility of using the OGI technique to detect leaks in hydrogen networks and installations resulted in the development of this technique through the use of tracer gas. First, tests were carried out using SF6 as a tracer. SF6 is a gas that absorbs infrared radiation very well, therefore it seems to be an ideal tracer for OGI techniques, however, due to its high GWP (approx. 23,000), other tracers were searched in parallel [18]. Currently, carbon dioxide is a tracer added to hydrogen that enables the use of the OGI technique to detect leaks in networks and installations transporting clean hydrogen [18; 19, 20]. The research has shown that the addition of carbon dioxide to hydrogen in an amount below 5% allows for effective optical imaging of gas leaks from hydrogen transport installations.

Since methane is an infrared-active gas, it should be assumed that in the case of detecting leaks in gas networks transporting NG-H2 mixtures, methane will be a tracer allowing the use of the OGI technique. The use of such a solution, like the use of other methane detection systems, will increase the lower limit of detected leaks compared to leaks detected in natural gas networks. The advantage of this solution is that the equipment currently used by TSO and DSO operators will be able to continue to be used without changing the configuration or measurement method.

2.3.1 OGI - market review

An overview of OGI devices available on the market is presented in the Table 2.5.

The research leading to these results has received funding from Horizon Europe, the European Union's Framework Programme for Research and Innovation under grant agreement n° 101111888.

Table 2-4: Optical Gas Imaging devices

manufacturer	model	gas detected	thermal sensitivity	wavelength
FLIR	GF343	CO_2	no data	4.2 – 4.4 µm
FLIR	GF346	CO	no data	4.52 – 4.67 µm
FLIR	GF620	C_xH_y	no data	3.2 – 3.4 µm
FLIR	GF320	C_xH_y	methane: 0.6 g/hr	3.2 – 3.4 µm
FLIR	GF77	CH_4, SO_2, N_2O	methane: 2.7 g/h	7.0 – 8.5 µm
FLIR	GF306	SF_6, NH_3	sulfur hexafluoride: 0.026 g/hr ammonia: 0.127 g/hr	10.3 – 10.7 µm
Opgal	EyeCGas® Multi	C_xH_y	methane: 0.07 g/hr	3,1 - 4,4 µm or 3,2 - 3,5 µm or 3,3 - 3,6 µm or 4,1 - 4,4 µm
ICI	OGI Inspector	C_xH_y	methane: 0.75 g/hr	3,2- 3,4 µm
ICI	Gas DetectIR VOC	C_xH_y	methane: 0.75 g/hr	3 - 5 µm
ICI	Gas DetectIR LW	SF_6	no data	10 - 11 µm
ICI	Mirage HC	CxHy	methane: 0.75 g/hr	3.2 - 3.4 µm
Sensia	Caroline X	SF_6	no data	no data
Sensia	Caroline Y	CH_4	no data	no data
Sensia	Mileva 33F	C_xH_y	methane: 0,4 g/hr	no data
Sensia	Mileva 45F	CO_2	carbon dioxide: 3,24 g/hr	no data
Telops	Hyper-Cam iMWF	C_xH_y	no data	3.0 – 5.0 µm
Sierra Olympia	Ventus OGI™	C_xH_y	60 g/hr	3.0 – 5.0 µm

OGI devices available on the market allow the detection of hydrocarbons, including methane, as well as substances that can be used as hydrogen tracers.

2.4 Acoustic methods

Leak detection using acoustic emission (AE) sensors is a technology that can detect and locate gas leaks even from small cracks or perforations in gas networks [21, 22]. Acoustic emissions associated with leaks in gas infrastructure are caused by the turbulent outflow of a high-pressure gas stream through the hole that constitutes the leak. In the case of underground infrastructure (gas pipelines), acoustic sensors placed along the pipelines are used to detect leaks. In the acoustic leak localization method, acoustic sensors are key

The research leading to these results has received funding from Horizon Europe, the European Union's Framework Programme for Research and Innovation under grant agreement n° 101111888.

components of the system, so the selection of a sensor should be based on the frequency range and propagation characteristics of the signal generated by the leak. In general, the choice of acoustic sensors is a choice between high-frequency and low-frequency sensors. High-frequency sensors have the distinct advantage of being immune to ambient noise, which usually propagates in the low-frequency range. However, due to the fact that high-frequency signals are heavily attenuated during propagation, monitoring gas pipelines of considerable length with them is difficult [21, 23]. Detecting the location of a leak using acoustic sensors is done similarly to the NPW method, with pressure sensors replaced by acoustic sensors. The leak detection system calculates the leak location based on the speed of sound propagation and the arrival time of the acoustic signal to two adjacent acoustic sensors, according to equation (2-4) [23]:

$$x = \frac{L + c\Delta t}{2} \quad (2\text{-}4)$$

where:

- x is the distance between the leak point and the upstream acoustic sensor (m),
- L is the distance between upstream and downstream sensors (m),
- Δt is the time interval between upstream and downstream sensors received (s),
- c is propagation velocity of acoustic signal in medium (m/s).

The principle of operation of the acoustic method is shown in the fig. 2-2.

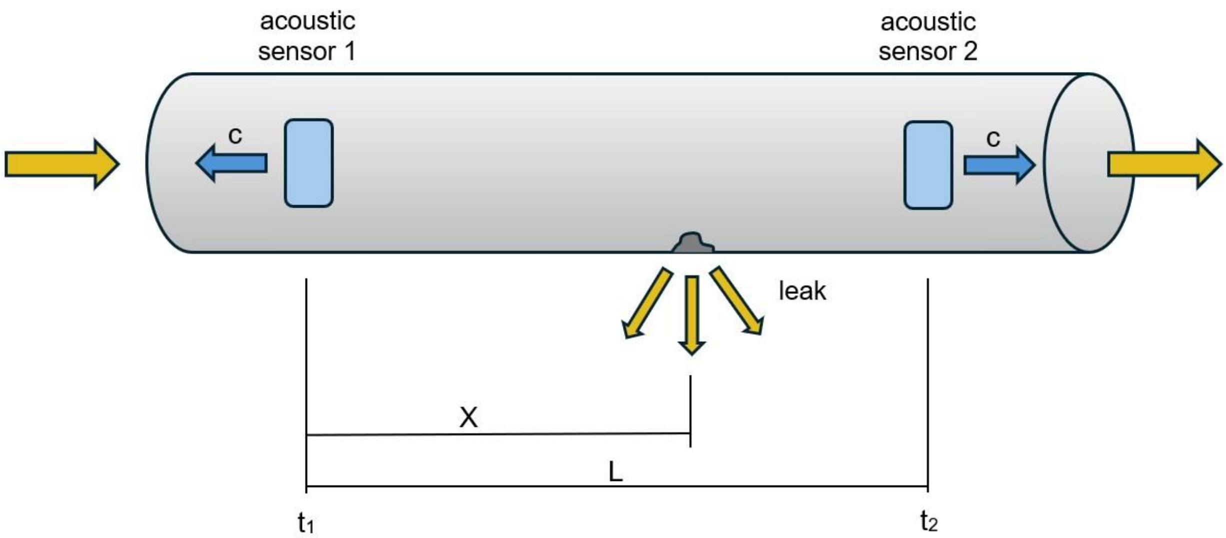

Figure 2-2: Schematic diagram of acoustic leak detection system (based on [23]

Compared with other pipeline leak detection techniques, the acoustic sensor technique has the advantages of non-invasiveness, low cost, simple design and high sensitivity. At the same time, it has all the disadvantages of the NPW technique, which are mainly due to the fact that the speed of sound propagation in the medium depends on the composition of that medium. Thus, this method will locate leaks in gas networks transporting NG-H2 mixtures with good accuracy, regardless of the hydrogen content of these mixtures, as long as this content remains constant over time.

Acoustic methods are also used to detect leaks in above-ground infrastructure. In this case, portable acoustic imaging (AGI) devices are used, whose surface consists of dozens of sensors listening to the sound field of a selected element or group of elements. Differences in the sound waves received by the device are used to locate the sources of emission and present them as an image. The sensitivity and accuracy of the devices depends on both the number of ultrasonic sensors and their mutual arrangement, as well as the data processing algorithms

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used [24]. Devices of this type can detect multiple leaks simultaneously, but they are not immune to ambient noise, as well as to ultrasonic reflections from steel elements of the inspected installation, which can cause false signals.

2.4.1 AGI - market review

None of the TSO and DSO operators involved in the SHIMMER project declared that they currently use acoustic methods. Based on this, it should be assumed that gas networks are not equipped with acoustic sensors, and their installation would require uncovering the gas pipeline. For this reason, the market review focused on portable acoustic gas imaging devices that can be used to detect leaks in the above-ground part of the gas network. Table 2-5 shows the characteristics of devices available on the market.

Table 2-5: Acoustic Gas Imaging devices

manufacturer	model	range	distance
DISTRAN	Ultra Pro	down to 0.005 l/min at 4 bar, from 0.3 m	0.3-100 m
FLIR	Si124	down to 0.016 l/min at 1.2 bar, from 0.3 m	0.3-130 m
HIKMICRO	Al56	down to 0.008 l/min at 6 bar, from 0.5 m	0.3-150 m
FLUKE	ii900	down to 0.15 l/min from 10 m	0.5-70 m
SDT	SonaVou	down to 0.05 l/min at 0.25 bar, from 1 m	0.3-50 m

The data presented in Table 2-5 show that the measuring range of the devices depends on both the distance from which the measurements are made and the overpressure in the network. Therefore, without testing in similar conditions, it is difficult to compare the capabilities of individual devices.

2.5 Laser methods

Two types of lasers are used to detect methane emissions: LIDAR and diode lasers. The LIDAR technique using a pulsed laser emitting at two wavelengths. This instrument measures the light that is scattered and reflected from the Earth's surface and cloud tops which are illuminated by laser pulses with slightly different wavelengths: λon (1.16455 mm) and λoff (1.16458). The online wavelength λon is positioned on one of the CH4 absorption lines at 1.64 µm. The measurement at λoff serves as the reference measurement with negligible absorption by the CH4 molecules in the path [25]. The second type of lasers used to detect methane emissions are diode lasers. Semiconductor lasers that are mainly made of gallium arsenide, indium phosphite, antimonides and lead salt have spectral ranges that extend from the visible to the infrared regions. Semiconductor diode lasers have been widely used for applications involving absorption spectroscopy. Such lasers have been used for detecting species with absorption bands in the near-infrared region, such as CO2 at 1604 nm, water vapour at 1303 nm and CO at 1604 nm, NO at 1800 nm and CH4 at 1650 nm [26]. Both laser systems used to detect methane leaks use the absorption of IR radiation by methane molecules. Due to the fact that hydrogen is an inactive gas in infrared light, these systems cannot be used to detect leaks in pipes transporting pure hydrogen. In the case of gas networks transporting mixtures of hydrogen and natural gas, it is possible to use laser systems, but their sensitivity will be lower than sensitivity for natural gas. Leak detection in hydrogen networks using laser methods is possible, in which case tunable diode laser are used [27, 28]. For the detection of hydrogen using diode lasers, solutions using wavelengths of 2121.83 nm, characteristic for hydrogen, are used. The absorption of waves with a length of 2121.83 nm by hydrogen molecules is relatively weak, therefore solutions that increase the length of the optical path are used in measurements [27]. Laser leak detection techniques in hydrogen networks should be classified as low TRL techniques for which there are no commercial solutions on the market.

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3 Quantification/measurement of hydrogen emissions

Various measurement methods are used to quantify methane emissions from gas networks. These methods can be used, with certain limitations, to quantify methane and hydrogen emissions when transporting mixtures of natural gas and hydrogen or pure hydrogen. The methods considered in this chapter are:

- correlation method described in the EN 15446:2008 Fugitive and diffuse emissions of common concern to industry sectors - Measurement of fugitive emission of vapours generating from equipment and piping leaks,
- airflow method - concentration and flow rate measurement,
- computational methods,
- bagging,
- optical gas imaging,
- acoustic imaging.

3.1 Correlation method

The method described in the standard EN 15446:2008 involves measuring the concentration of methane in the air (in ppm) in the vicinity of the leaking element. The maximum measurement result obtained in this way is converted into volume flow using the correlation coefficients given in the standard [29]. Due to the different physico-chemical properties of methane and hydrogen, including, above all, density, molecular weight and size, the correlation method should not be used for hydrogen and natural gas-hydrogen mixtures until dedicated correlation equations for hydrogen are developed. In the future, the use of the correlation method for natural gas - hydrogen mixtures may require independent measurement of the concentration of both components in the air. It should be assumed that the place where the maximum methane content occurs will be different from the place where the maximum hydrogen concentration occurs.

3.2 Airflow method

The combined measurement of the methane concentration in the air sucked in from the surroundings of the leaking element and the air flow velocity allows for an accurate measurement of the emission level [30]. In the case of methane, there are devices on the market dedicated to this purpose. Analogous devices for hydrogen are under development. Currently, measurement of pure hydrogen emissions using the airflow method can only be performed using a set of devices:

- fan or aspirator,
- device for measuring low hydrogen concentrations,
- gas meter.

This way of implementing the air flow emission measurement method is technically difficult to implement.

In the case of natural gas - hydrogen mixtures, it is possible to measure methane emissions with available devices and then estimate the hydrogen emission level based on the composition of the mixture, in accordance with equation 3-1:

$$E_{H2} = \frac{E_{CH4} \cdot C_{H2}}{C_{CH4}} \quad (3\text{-}1)$$

where:

- E_{H2} is hydrogen emission (l/min),
- E_{CH4} is methane emission (l/min),
- C_{H2} is the concentration of hydrogen in the natural gas-hydrogen mixture (% mol/mol),
- C_{CH4} is the concentration of methane in the natural gas-hydrogen mixture (% mol/mol).

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Measurements of methane and hydrogen emissions using the airflow method performed using devices dedicated to measuring methane emissions will be characterized by:

- the same limit of quantification for methane regardless of whether the measurement is carried out for natural gas or for natural gas - hydrogen mixtures,
- the limit of quantification of hydrogen emissions is equal to the limit of quantification of methane emissions multiplied by the ratio of hydrogen and methane concentrations in the mixture.

3.3 Computational methods

In the category of computational methods, there are three methods that are dedicated to measuring methane emissions from gas pipelines. These methods are:

- the method of measuring the pressure drop in an isolated section of a gas pipeline
- direct measurement method, which requires maintaining constant gas pressure in a section of the leaking gas pipeline isolated from the rest of the network,
- the pressure variation method, which uses the principle that the rate of gas flow at the leak site is proportional to the gas pressure prevailing in the network.

For the correct implementation of any of these methods, it is necessary to ensure that gas from the section in question is not withdrawn by recipients during the measurements or that the withdrawal is constant over time. The most difficult to implement in real conditions is the method based on measuring the pressure drop, as this method requires complete isolation of the section of the gas pipeline under test. The isolated section of the pipeline is then filled with gas to a certain pressure, after which the gas pressure drop in the pipeline is measured at certain intervals. The rate of pressure drop is a function of the rate of gas outflow through leaks located in the section. The gas medium with which the measurements are made can be either natural gas or hydrogen or a mixture thereof or inert gas [31, 32]. The direct measurement method is also not very resistant to possible changes in the volume of gas consumption by individual recipients, so it should be carried out with complete isolation of the section of the gas pipeline under study. In such a situation, gas is injected into the isolated section of the pipeline in order to achieve a pressure close to the working pressure prevailing on the pipeline section. The amount of gas injected into the pipeline necessary to maintain constant gas pressure in the pipeline is then measured. Measurements using this method can also be carried out while maintaining uniform gas intake from the network. In this case, it is required not only to measure the amount of gas injected into the network to maintain constant pressure, but also to measure the amount of gas delivered to recipients. In real conditions, the implementation of this method in the variant with maintenance of gas consumption by recipients is feasible only in the case of such sections of gas pipelines to which single industrial recipients are connected who consume constant amounts of gas over time [32].

In terms of computational methods, the method based on the use of the relationship of gas flow rate to pressure seems to have the widest applicability. This method assumes a near-linear dependence of the volume of gas outflow on the pressure prevailing in the pipeline. The implementation of methane emission measurements by this method is based on three basic steps [31, 32]:

- **Step 1 -** measurement of gas flow rate in the pipeline under different pressure conditions, this measurement is made at the entrance of the pipeline section under study. Based on the results obtained, the dependence of gas flow rate on pressure is plotted.
- **Step 2 -** estimation of gas consumption by consumers, this value is estimated by linear extrapolation of the values measured in step 1 to the intersection with the Y axis. Analysis of the possibility of estimating the amount of methane emissions from the natural gas network
- **Step 3 -** estimation of the volume of gas emissions from the leaking section of the gas pipeline, this value is the difference between the interpolation-determined value of the gas flow rate (GF_{total}) and the estimated gas consumption of consumers ($GF_{consumers}$).

The principle of the method based on the use of the relationship of gas flow rate to pressure is shown in Figure 3-1.

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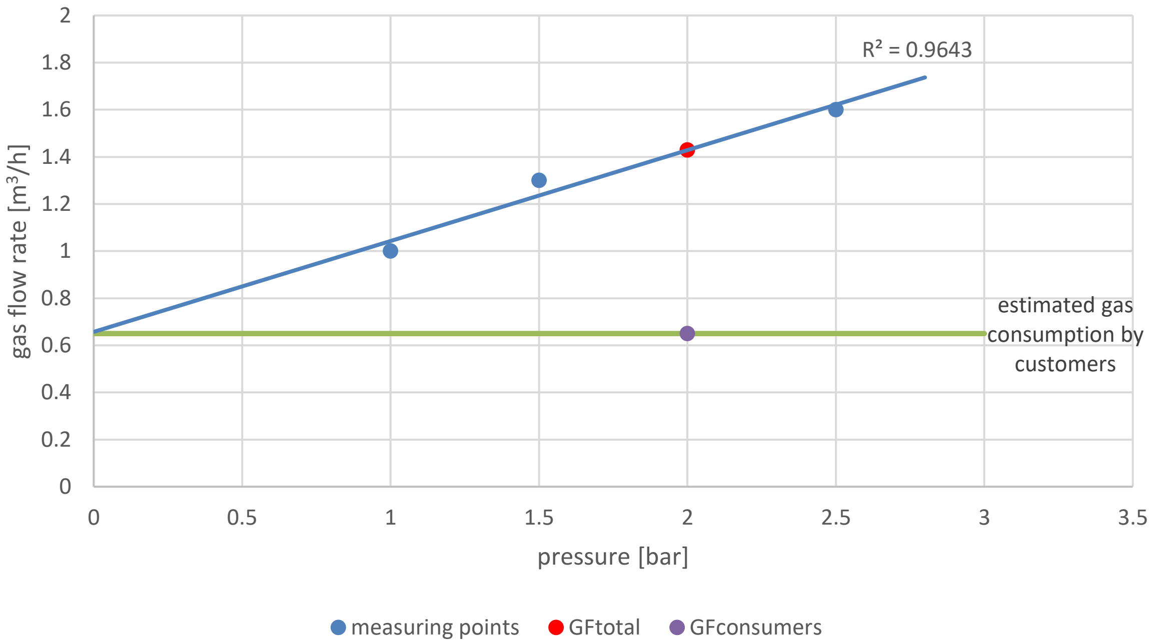

Figure 3-1: Determining the result in a pressure variation method [32]

The last of the described balance methods places the least restrictive requirements on the need to isolate a given section of the pipeline. Measurement by this method can be carried out on a section of the gas pipeline that has not been taken out of service, which is a significant advantage. It should be borne in mind that the uncertainty in the determination of methane emissions, will largely depend on the maintenance of constant gas consumption by consumers [31, 32]. Unfortunately, this parameter is difficult to control under real-world conditions, and large daily variations in the amount of gas consumed by customers may disqualify this method as a method for estimating methane emissions.

Analyzing the information on balance methods, it can be concluded that these are methods that are used to estimate the amount of methane emissions from leaking gas pipelines. However, these methods cannot be called measurement methods, especially when there is no complete isolation of the gas pipeline under study. However, these methods also have an important advantage. This is that they do not require prior location of the leak site. In addition, balance methods make it possible to estimate the total volume of methane emissions from a given section of a gas pipeline, even in cases where it contains more than one leak.

3.4 Bagging

Bagging methods allow to measure emissions directly. There are currently two bagging methods:

- vacuum bagging
- blow through

In both methods the emission rate of a component is measured by bagging the component with an impermeable foil constructed of inert material and evacuating the undiluted leak from the bag at a constant measured flow rate [33].

The measurement method using the vacuum method is shown in Figure 3-2.

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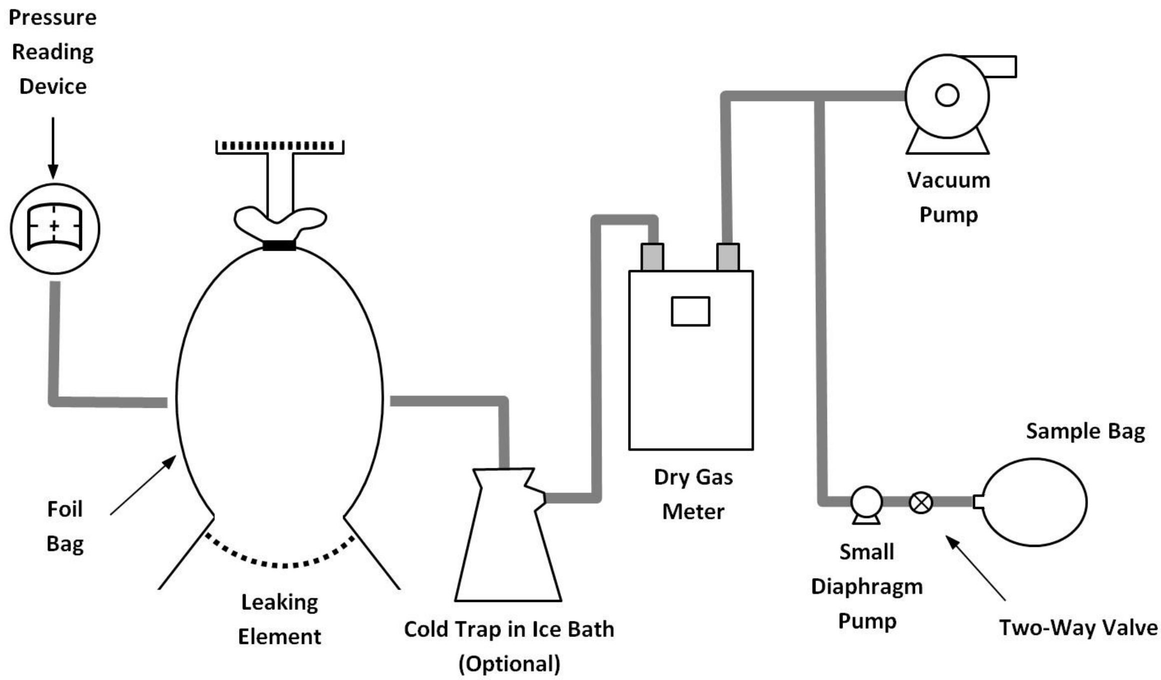

Figure 3-2: Schematic diagram of the vacuum bagging method (based on [33, 34])

The most important elements of the system used for emission measurements using the vacuum method are a gas-tight bag covering the leaking element, a vacuum pump ensuring air flow through the system and a gas meter used to measure the flow rate of gas through the system [34]. Hydrogen emission is calculated based on the equation 3-2:

$$E_{H2} = \frac{9.63 \cdot 10^{-10} \cdot Q \cdot M \cdot C \cdot P}{T} \tag{3-2}$$

where:

- E_{H2} is hydrogen emission (kg/h),
- Q is flow rate out of bag (l/min),
- M is molecular weight (kg/kmol),
- C is sample bag hydrogen compound concentration (ppm),
- P is absolute pressure at the dry gas meter (mmHg),
- T is temperature at the dry gas meter (K).

The measurement method using the blow through method is shown in Figure 3-3.

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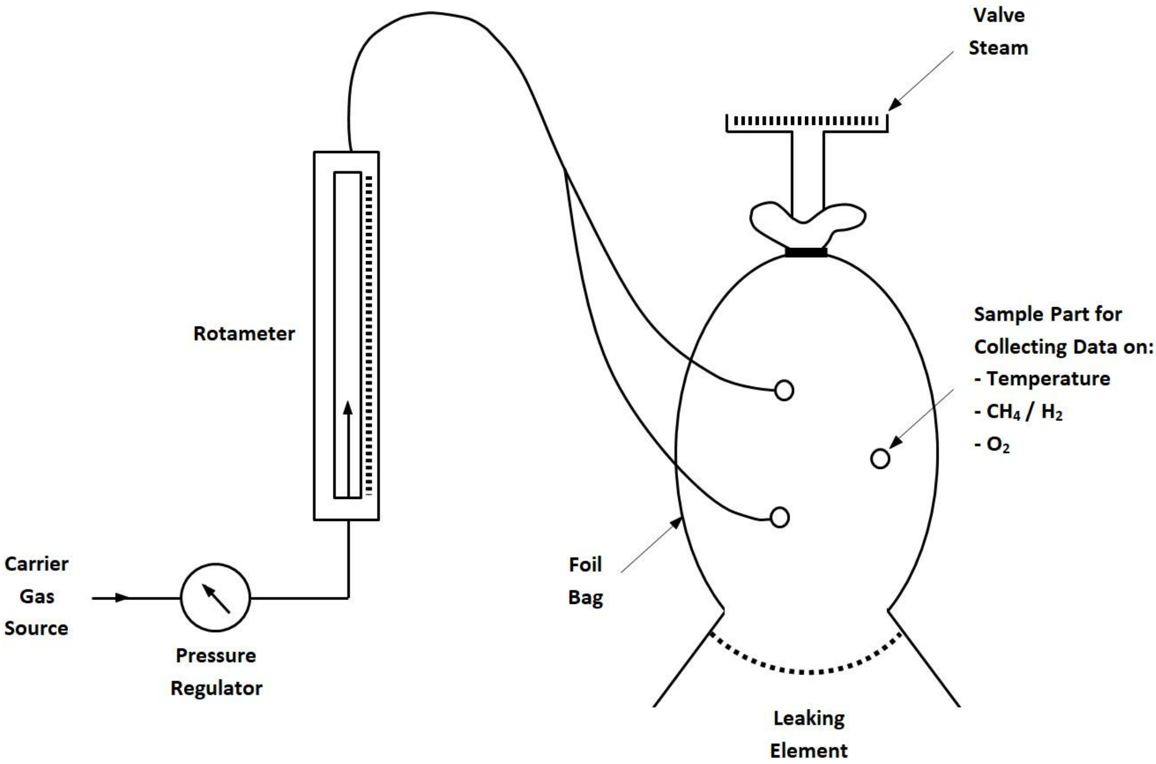

Figure 3-3: Schematic diagram of the blow through method (based on [34])

In the blow through method carrier gas is metered into the bag through tubes. The flow rate of the carrier gas is monitored in a gas rotameter. The carrier gas flow rate should be set to a constant rate and kept at that rate long enough for the system to reach equilibrium. Once the bag contents are at steady state, two gas samples are drawn out of the bag for laboratory analysis using a portable sampling pump [34]. Hydrogen emission is calculated based on the equation 3-3:

$$E_{H2} = \frac{1.219 \cdot 10^{-5} \cdot Q \cdot M \cdot C}{T} \quad (3\text{-}3)$$

where all symbols are the same as in equation 3-2.

Both variants of the bagging method were developed by the EPA in the 1990s, currently the gas composition in the gas-tight bag can be determined using portable devices and not, as recommended by the EPA, based on laboratory analyses. Although the method was developed for VOC measurements, it can be used to measure both the emission of pure hydrogen and its mixtures with natural gas as long as measuring devices (gas meter, rotameter) appropriate for the given type of gas are used.

3.5 Optical gas imaging

The QOGI technique uses optical imaging and special computational algorithms to quantify the emission of a given gas. When measuring emissions using the QOGI technique, three factors affect the feasibility of measurements (Figure 3-4) [35]:

- IR absorption α(λ) — the gas to be detected must have an IR absorption peak that overlaps with the spectral window of the OGI camera. As mentioned in section 2.4, hydrogen is an inactive gas in the

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infrared, therefore the QOGI technique can only be used for NG-H2 mixtures. In this case, only methane emissions will be measured, while hydrogen emissions can be estimated based on the mixture composition and measured methane emissions.

- Delta temperature ΔT — there must exist sufficient temperature differential between the gas leak and the background. The minimum temperature difference between the gas leak and the ambient temperature should be 2 °C [36].
- Gas Presence ɠ — here must be gas present in the image that is greater than the minimum detection limit of the system.

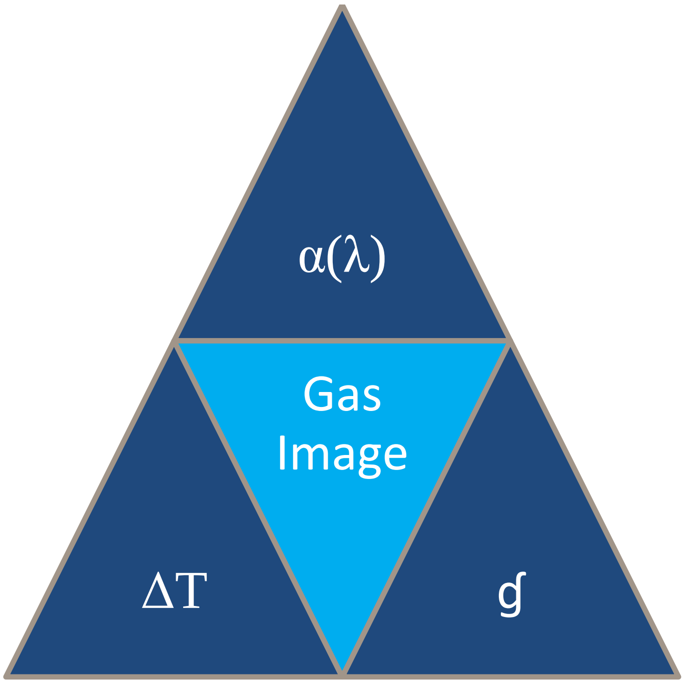

Figure 3-4: Factors affecting gas image in an OGI camera [35]

In the case of both qualitative (leak detection) and quantitative (emission measurement) OGI techniques, an increase in the hydrogen content in the NG-H2 mixture will result in an increase in the detection limit and quantification limit.

3.6 Acoustic imaging

Most acoustic cameras allow you to determine gas flow rate on the sound source loudness. Measurement of gas emissions in litres/minute takes place in real time. The accuracy of measurements and the limits of quantification are greatly influenced by ambient noise. For this reason, acoustic methods should not be used for those elements of the gas grid that are accompanied by noise, e.g. compressed stations. Due to the measured physical parameter, which is the noise generated during gas expansion, the acoustic emission measurement method is a universal method and can be used both to measure emissions of pure hydrogen and methane, as well as their mixtures. If the acoustic method is used to measure emissions from gas networks transporting the NG-H2 mixture, the measurement result will be the sum of the emissions of both components of the mixture.

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4 Methods ranking list

The methods for detecting leaks and measuring hydrogen emissions were assessed taking into account the following aspects:

- type of detected/measured gas,
- resistance to changes in gas composition,
- availability of measuring devices,
- cost of purchasing and maintaining the equipment,
- scope of application,
- staff qualifications,
- other advantages and disadvantages.

Each aspect was assessed on a five-point scale of 1-5, where 1 is the lowest score and 5 is the highest score. The ranking of methods was performed separately for the emission detection and measurement method.

4.1 Leak detection methods

Table 4-1 presents an evaluation of the individual leak detection methods along with their justification.

Table 4-1: Leak detection methods – ranking list

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Aspect	Description	Rating
Sniffers		
Type of detected gas	• only methane or hydrogen, • both gases switchable or simultaneously. Different device configurations allow measurement of one or both types of gas. Devices can be used for both pure gases and NG-H2 mixtures	5
Resistance to changes in gas composition	• resistant to changes in gas composition, • changes in composition may affect the lower limit of leak detection (see Table 2-4)	4
Availability	• high availability, • there are dozens of device manufacturers, • different device configurations are available	5
Costs for purchasing device and implementing method	• low purchase cost (up to 5,000 Euro) • low operating costs related to periodic calibration, filter and battery replacement,	5
Scope of application	• for both distribution and transmission networks • only above ground elements or exposed underground elements • only elements that can be accessed directly	4
Staff qualifications	• easy to use, • typical device used by operational services	5
Other	+ mostly devices intended for explosion hazard zones + light and small - leak detection is time consuming	3
Computational leak detection methods		
Type of detected gas	• can be applied to both pure gases and mixtures, • correct use requires knowledge of the physicochemical parameters of the gas or mixture	4
Resistance to changes in gas composition	• not resistant to changes in gas composition, • changes in gas composition require recalibration of the method	1
Availability	• they use data measured from the gas network • may not require additional measuring devices than those typically installed on the network • may require the implementation of special computational algorithms	4
Costs for purchasing device and implementing method	• difficult to determine cost, • the cost depends on the network configuration, available data, and the chosen method of implementation	3

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Scope of application	• both the distribution and transmission networks • both above ground and underground elements (mainly gas pipelines)	5
Staff qualifications	• requires personnel who know the operating conditions of a given network	4
Other	+ allows for continuous monitoring of leaks + low time and work expenditure - in some variants it may be difficult to precisely determine the location of the leak	4
Optical gas imaging		
Type of detected gas	• hydrogen is inactive in IR • hydrogen leak detection requires the use of a tracer • in the case of NG-H2 mixtures, the tracer may be methane	2
Resistance to changes in gas composition	• changes in composition may affect the lower limit of leak detection	4
Availability	• there are several devices available from different manufacturers • not all devices are intended for use in explosion hazard zones	2
Costs for purchasing device and implementing method	• expensive (purchase cost approx. 75-100 k€)	2
Scope of application	• both the distribution and transmission networks • above ground elements • can be used for hard-to-reach places	4
Staff qualifications	• requires specialized staff • staff experience improves the quality of the inspection and shortens its duration	3
Other	+ short inspection time + possibility of using one device for leak detection and emission measurement	5
Acoustic gas imaging		
Type of detected gas	• all types of pressurized gases	5
Resistance to changes in gas composition	• resistant to changes in gas composition	5
Availability	• there are several devices available from different manufacturers • not all devices are intended for use in explosion hazard zones	2

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Costs for purchasing device and implementing method	• quite expensive (purchase cost below 50 k€)	3
Scope of application	• both the distribution and transmission networks • above ground elements • can be used for hard-to-reach places	4
Staff qualifications	• requires specialized staff • staff experience improves the quality of the inspection and shortens its duration	3
Other	+ short inspection time + possibility of simultaneous leak detection and emission measurement - not resistant to ambient noise	4

The method using sniffers received the highest score, obtaining a total of 31 points, the remaining methods received:

- 26 points – acoustic methods,
- 25 points – computational methods,
- 22 points – optical methods.

What is important, however, is that in different aspects, individual methods were rated with different numbers of points (Figure 4-1).

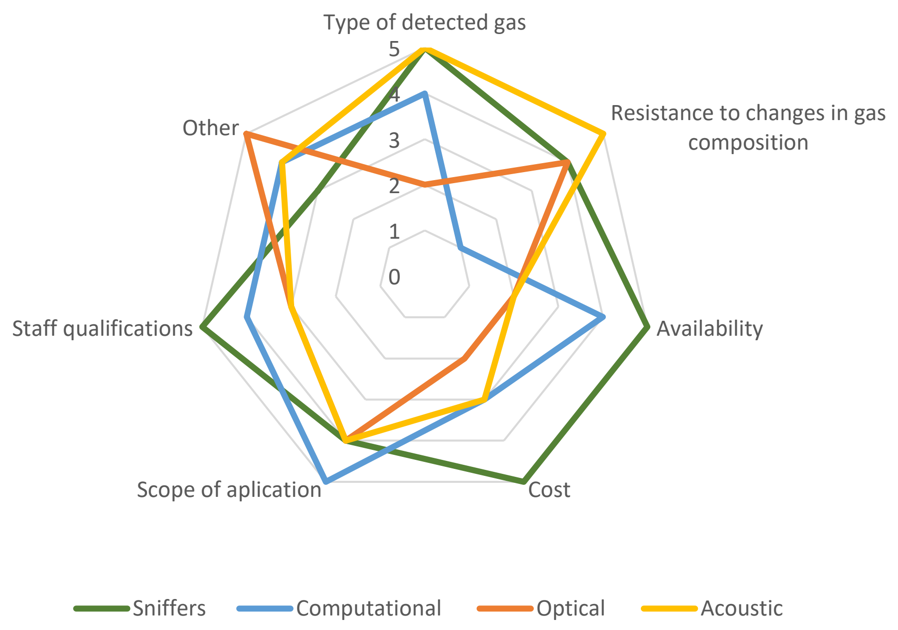

Figure 4-1: Evaluation of leak detection methods in various aspects

Taking into account the data presented in Figure 4-1, it is not possible to indicate a universal method for detecting leaks in gas networks transporting NG-H2 mixtures. Each of the methods considered has advantages

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and disadvantages, as well as the optimal area of application of a given method. It should be assumed that, as in the case of leak detection monitoring of natural gas networks, monitoring networks transporting NG-H2 mixtures will require the use of various measurement methods.

4.2 Quantification/measurement emissions methods

Table 4-2 presents an evaluation of the individual measurement emissions methods along with their justification.

Table 4-2: Quantification/measurement emissions methods– ranking list

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Aspect	Description	Rating
Correlation method		
Type of detected gas	• only methane, • the application of correlation methods to hydrogen requires the development of appropriate coefficients factors	1
Resistance to changes in gas composition	• resistant to changes in gas composition,	5
Availability	• high availability, • there are dozens of device manufacturers,	5
Costs for purchasing device and implementing method	• low purchase cost (up to 5,000 Euro)	5
Scope of application	• both the distribution and transmission networks • only above ground elements or exposed underground elements • only elements that can be accessed directly	4
Staff qualifications	• the method of conducting measurements affects the results obtained	3
Other	- the method cannot be applied to hydrogen and NG-H2 mixtures until correlation coefficients are developed	1
Airflow method		
Type of detected gas	• can be applied to pure methane and NG-H2 mixtures	4
Resistance to changes in gas composition	• resistant to changes in gas composition, • changes in composition may affect the lower limit of leak detection • requires knowledge of the composition of the NG-H2 mixture	4
Availability	• few devices are available to measure methane emissions • measurement of pure hydrogen emissions using the airflow method can only be performed using a set of devices	2
Costs for purchasing device and implementing method	• quite expensive (purchase cost below 50 k€)	3
Scope of application	• both the distribution and transmission networks • both above ground and underground elements	5
Staff qualifications	• ease of measurement • extensive experience is not required to conduct measurements	5

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Other	+ resistant to weather conditions - requires prior determination of the location of the leak	4
Computational methods		
Type of detected gas	• can be applied to both pure gases and mixtures	5
Resistance to changes in gas composition	• resistant to changes in gas composition	5
Availability	• they use data measured from the gas network • may not require additional measuring devices than those typically installed on the network • may require the implementation of special computational algorithms	4
Costs for purchasing device and implementing method	• difficult to determine cost, • the cost depends on the network configuration, available data, and the chosen method of implementation	-
Scope of application	• both the distribution and transmission networks • easier to use in transmission networks with a small number of customers • both above ground and underground elements (mainly gas pipelines)	4
Staff qualifications	• requires personnel who know the operating conditions of a given network	4
Other	+ allows for continuous monitoring of emissions + low time and work expenditure - the quantification result depends on the ability to maintain stable gas consumption conditions	4
Bagging		
Type of detected gas	• can be applied to both pure gases and mixtures	5
Resistance to changes in gas composition	• resistant to changes in gas composition	5
Availability	• requires the use of easily accessible devices • various types of devices are required to implement the method	4
Costs for purchasing device and implementing method	• low cost of purchasing devices • may require the use of a carrier gas	4

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Scope of application	• both the distribution and transmission networks • only above ground elements • only elements small enough to be packed tightly	3
Staff qualifications	• the team's experience allows us to shorten the measurement time • the need to monitor several parameters simultaneously requires a 2-3 person team to carry out the measurement	3
Other	- requires prior determination of the location of the leak - correct preparation of the element for measurement is time-consuming	2
Optical gas imaging		
Type of detected gas	• hydrogen is inactive in IR • hydrogen leak detection requires the use of a tracer • in the case of NG-H2 mixtures, the tracer may be methane	2
Resistance to changes in gas composition	• changes in composition may affect the lower limit of quantification	4
Availability	• there are several devices available from different manufacturers • not all devices are intended for use in explosion hazard zones	2
Costs for purchasing device and implementing method	• expensive (purchase cost approx. 75-100 k€)	2
Scope of application	• both the distribution and transmission networks • above ground elements • can be used for hard-to-reach places	4
Staff qualifications	• requires specialized staff • staff experience improves the quality of measurements	3
Other	+ short inspection time + possibility of using one device for leak detection and emission measurement	5
Acoustic gas imaging		
Type of detected gas	• all types of pressurized gases	5
Resistance to changes in gas composition	• resistant to changes in gas composition	5
Availability	• there are several devices available from different manufacturers • not all devices are intended for use in explosion hazard zones	2

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Costs for purchasing device and implementing method	• quite expensive (purchase cost below 50 k€)	3
Scope of application	• both the distribution and transmission networks • above ground elements • can be used for hard-to-reach places	4
Staff qualifications	• requires specialized • staff experience improves the quality of measurements	3
Other	+ short inspection time + possibility of simultaneous leak detection and emission measurement - not resistant to ambient noise	4

The airflow method received the highest score, obtaining a total of 27 points, the remaining methods received:

- 26 points - acoustic methods, bagging and computational methods
- 24 points – correlation,
- 22 points – optical methods.

What is important, however, is that in different aspects, individual methods were rated with different numbers of points (Figure 4-2).

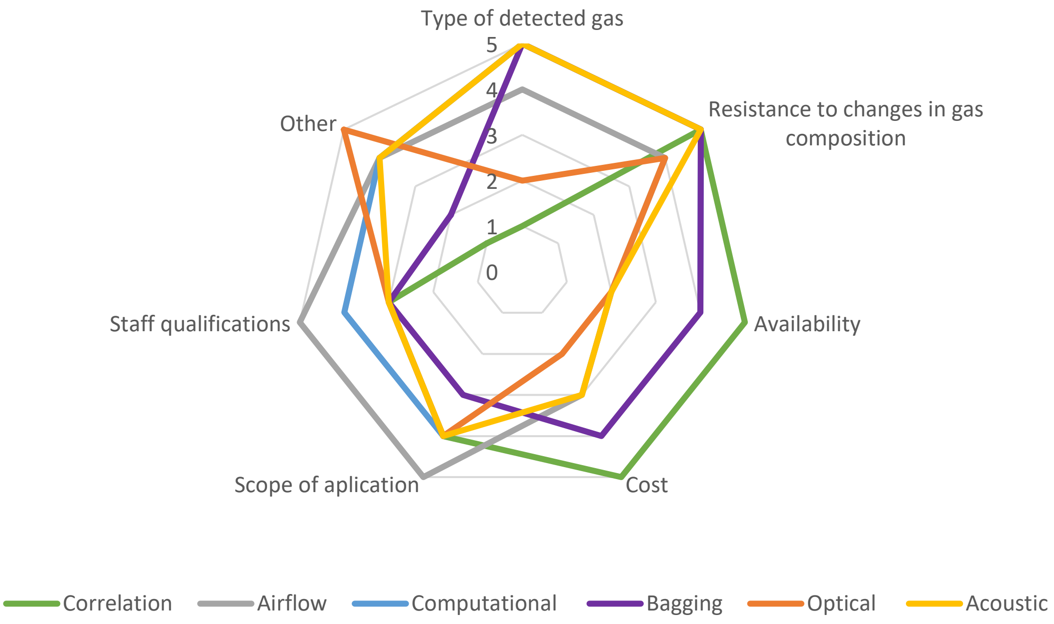

Figure 4-2: Evaluation of emissions measurement methods in various aspects

As in the case of leak detection methods, each method of measuring and estimating emissions has different advantages and disadvantages. Therefore, it is not possible to indicate one optimal method for measuring GHG emissions from networks transporting NG-H2 mixtures. The choice of the appropriate method depends on the measurement conditions.

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5 Conclusions

TSO and DSO operators use different methods of detecting leaks and measuring methane emissions from gas networks. Replacing the existing networks transporting natural gas with networks transporting NG-H2 mixtures will require a change in the method of monitoring leaks and measuring methane.

Based on the analysis carried out, it can be concluded that most of the methods used to detect leaks can be used with the same effect for networks transporting natural gas and networks transporting NG-H2. However, changing the transported medium may affect the lower detection limit of the method. This situation applies to the use of sniffers or optical gas imaging for leak detection. The most difficult thing will be to transfer the experience in leak detection using computational methods from natural gas networks to networks transporting NG-H2 mixtures. This is due to the fact that changes in the gas composition affect the physicochemical properties of the gas mixtures and require recalibration of the computational algorithms.

Most of the methane emission measurement methods used by TSO and DSO operators will still be able to be used for NG-H2 mixtures. Based on the measurement results obtained for methane, it is possible to estimate hydrogen emissions. The exception is the correlation method, the use of which first requires the development of correlation coefficients dedicated to hydrogen.

For both leak detection and emission measurement methods, no single optimal method can be identified. All mentioned methods are characterized by various advantages and disadvantages, which means that, depending on the measurement conditions, different methods may be optimal.

Carrying out tests in laboratory conditions in the next stage will confirm the scope of application of individual methods and their resistance to changes in the composition of the transported mixture.

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A Appendix A: Sniffers - market review

manufacturer	model	gas detected	sensor type	range
Sniffers only for methane				
Alarm-Ex	Alex D/02	methane	electrochemical	0,1-25% v/v
Alter	LD-100 Ex	methane	semiconductor	100 – 10000 ppm
Alter	GD-8	methane	semiconductor	1%v/v – 40% LEL
Amprobe	GSD600	methane	semiconductor	40-640 ppm
BACHARACH	LEAKATOR-10	methane	semiconductor	above 20 ppm
Duomo	HHGAS	methane	semiconductor	40-640 ppm
Esders	Hunter	methane	semiconductor	0,1-100% v/v
Esders	SIGI EX	methane	no data	0-100% v/v
EWIMAR - WB	Multigas III Series	methane	catalytic	0-100% LEL
FIGARO	TGS 2611	methane	semiconductor	500-10000 ppm
GMI	PS200	methane	catalytic	0-100% LEL
Heath Consultants Incorporated	Detecto Pak-Infrared	methane	NDIR	1ppm-100%
Huberg	Rivelgas Plus	methane	electrochemical	0-100% LEL
Industrial Scientific	M40	methane	no data	0-100% LEL
Industrial Scientific	MX6 iBrid	methane	catalytic	0-5% v/v
Inficon	IRwin SX Methane Leak Detector	methane	NDIR	1-100% LEL
Neotronics	Minigas Mk5	methane	catalytic	no data
SENSIT Technologies	HXG-3P	methane	semiconductor	1-100% LEL
Sewerin	Variotec 450-Ex	methane	TCD	1-100% LEL
Sewerin	EX-TEC PM4	methane	semiconductor catalytic TCD	0-22000 ppm 0-100% LEL 0-100% v/v
Sewerin	EX-TEC PM 500 - series	methane	NDIR	0-100% LEL
Sewerin	EX-TEC HS 600 - series	methane	semiconductor/IR	0-100% v/v

manufacturer	model	gas detected	sensor type	range
Sewerin	PORTAFID M3K	methane	FID	1-10000 ppm
Southern Cross	Flame Pack 400	methane	FID	50 ppm
TELEDYNE	GMI series	methane	semiconductor	1-10000 ppm
TELEDYNE	GT Series	methane	semiconductor	1-10000 ppm
TELEDYNE	GT Series	methane	catalytic	1-100% LEL
TELEDYNE	GT Series	methane	TCD	1-100% v/v
Thermoscentific	TVA2020	methane	FID	0-50000 ppm
MSA	METER II	methane	catalytic	0-100% v/v
Sniffers only for hydrogen				
21Senses	Portable Hydrogen Leak Detector	hydrogen	electrochemical	up to 10% v/v
CENTER TECHNOLOGY CORP	CENTER 384	hydrogen	semiconductor	above 2 g/year
Cosmos	XP 3000 II	hydrogen	catalytic	100% LEL
Esders	HunterH2	hydrogen	no data	0-5% v/v
H2Scan	HY-ALERTA™ 500	hydrogen	catalytic	15 ppm - 100%
Inficon	Sensistor® XRS9012	hydrogen	no data	above 0.7 ppm
Inficon	Extrima®	hydrogen	no data	0.5 ppm - 0.2 %v/v
SENTRY OPTRONICS CORP	ST314A	hydrogen	semiconductor	above 1 ppm
Suzhou	H2SENSE Model 4000	hydrogen	no data	0.1-5%
Sniffers only for hydrogen or methane				
Edwards	GASCHECK G4	methane	mTCD	0.000002 ml/sec
Edwards	GASCHECK G4	hydrogen	mTCD	0.000005 ml/sec
Honeywell	GasAlertMicroClip XT	methane	catalytic	0-100% LEL
Honeywell	GasAlertMicroClip XT	hydrogen	catalytic	0-100% LEL
Honeywell	GasAlertMax XT or TX II	methane	catalytic	0-100% LEL
Honeywell	GasAlertMax XT or TX II	hydrogen	catalytic	0-100% LEL
Honeywell	MultiPro-series	methane	catalytic	0-100% LEL

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manufacturer	model	gas detected	sensor type	range
Honeywell	MultiPro-series	hydrogen	catalytic	0-100% LEL
Honeywell	QRAE-series	methane	catalytic	0-100% LEL
Honeywell	QRAE-series	hydrogen	catalytic	0-100% LEL
SHUETZ	Gas Pen Digital 3000 Ex	methane	semiconductor	0-50% LEL
SHUETZ	Gas Pen Digital 3000 Ex	hydrogen	semiconductor	0-50% LEL
Testo	316-2-EX	methane	no data	10 ppm - 4%
Testo	316-2-EX	hydrogen	no data	10 ppm - 4%
Sniffers for both gases (switchable)				
Cosmos	XP-702III-A	hydrogen	semiconductor	0.0000033 ml/sec
Cosmos	XP-702III-A	methane	semiconductor	0.0000033 ml/sec
Sniffers for both gases (simultaneously)				
Alter	GasHunter II	methane	Catalytic	up to 100% LEL
Alter	GasHunter II	hydrogen	electrochemical	up to 4% v/v
Dräge	X-am 5600	methane	IR	no data
Dräge	X-am 5600	hydrogen	electrochemical	no data
Honeywell	MultiRAE Lite	methane	IR	0-100% v/v
Honeywell	MultiRAE Lite	hydrogen	electrochemical	0-1000 ppm

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