Development of testing protocols for the measurement of pure and blended hydrogen in natural gas grids: An outlook from the THOTH2 project

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ABSTRACT

Transporting or blending hydrogen (H_2) into the existing gas infrastructure can be crucial in the European green transition. However, the regulation of this matter is still debated by interested stakeholders. The THOTH2 project aims to fill normative gaps by developing new protocols for assessing the limits and tolerances of state-of-the-art (SoA) instrumentation installed in natural gas (NG) transmission and distribution grids. This paper outlines the methodology used for selecting the devices and establishing the testing protocols for the various categories of instruments. These instruments are scheduled for experimental testing in the subsequent phase of the project.

1. Introduction

Hydrogen (H_2) is considered a versatile energy carrier because it efficiently transports energy converted from one form to another, even though it is not a primary energy source and can be used across multiple domains of energy usage, including the hard-to-abate and transportation sectors [1–3]. Furthermore, it is considered a carbon-free energy carrier because, when used as a fuel, its oxidation produces only water and energy, with no direct emissions of pollutants or greenhouse gases. Unfortunately, the processes applied for its production could have a substantial carbon footprint. The interest in H_2 derives from its capability to store renewable energy. Generally, H_2 could be stored as pressurised gas, as cryogenic liquid, or in solid-state form through physical or chemical bonding, offering versatile storage solutions [4,5]. In fact, many EU countries have implemented energy policies and funding incentives to promote the widespread integration of renewable energy sources (RES) into their energy systems in recent years. However, the fluctuating nature of electricity production from RES introduces challenges related to grid security and power balance. These challenges can be addressed using various types of energy storage solutions, including Power-to-Gas (P2G) and Power-to-Liquid (P2L) [6].

In the present context towards energy transition, there are various non-convergent trends, for example, towards increasing electrification or the establishment of a new H_2 economy [7]. The concept of an H_2 economy is based on the prospect of utilising H_2 as the predominant energy carrier. In the current framework, this concept is considered through the four interconnected phases of production, storage, safety, and utilisation. H_2 can be applied in the energy economy through stationary or mobile solutions. Stationary applications can be large-scale, operating at relatively high temperatures and pressure values [8], while mobile solutions could have a wider range of sizes. Hydrogen can be stored either at the end user side or at the production side. Stationary applications include, for example, the supply of areas far from the grid, backup power supply, and local power generation [9].

The transition to an H_2 economy involves addressing significant challenges, including clean production, infrastructure development, economic viability, and efficiency. However, this transition offers substantial opportunities to reduce greenhouse gas emissions and enhance energy security and sustainability.

Blending or transport green H_2 into the existing natural gas (NG) grids has an interesting potential for decarbonising the energy system and reducing greenhouse gas emissions due to its diverse applications in transport, electricity, heating, storage and grid services, and industrial use. However, as H_2 energy density per volume is one -third of NG, to transport the same amount of energy, faster flow rates of mixture would be required compared to NG. Consequently, this would result in changing the operating conditions [10]. That is, pipeline transmission appears to be the most economical means to transport considerable amounts of H_2 across long distances. Under adequate conditions and low H_2 concentrations, blending may require minimal modifications in the pipeline network operation and maintenance [11]. Minor issues may arise with H_2 blend fractions less than 5%–15%vol in NG, subject to specific site conditions and varying NG compositions, while higher concentrations would require additional evaluations about the effect of H_2 [12]. Particularly, H_2 effects on the State-of-the-Art (SoA) metrological components installed in NG distribution and transmission grids have been started to be investigated by the scientific community in several EU projects including, for example, NewGasMet [13], Met4H2 [14], THOTH2 [15]. Particularly, the THOTH2 project performed a literature review and a survey about the performances of the SoA measuring devices [16]. Furthermore, it depicted the normative status and roadmap to take into account modification due to the presence of hydrogen and natural gas mixtures (H2NG) and pure H_2 [17]. Starting from these results and the analysis of the measuring devices currently installed into the NG grids [18], including gas meters, pressure transmitters, trace water humidity sensors, and leak detectors, the paper aims to describe the methodology developed in the project to identify the measuring devices to be tested and the designed protocols. For this

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purpose, the paper is structured as follows. Section 2 illustrates the criteria for the selection of the devices to be tested. Section 3 describes the protocols' skeletons. Last, the conclusions show recommendations for the performance of the testing in the project.

2. Methodology

Starting from the knowledge developed about the measuring devices installed on the gas grids and the barriers against their use with H_2 [18], the THOTH2 project prioritized the measuring device to test and design new protocols to cover the remaining gaps in the literature. Some examples exist of NG transmission and distribution grids operated with H2NG mixtures or pure H_2. However, to assess the impact of H_2 in SoA measuring devices, the THOTH2 project includes experimental assessment in laboratory test benches. This approach would ensure a more complete picture since the results would not be affected by the specific operating conditions derived from end-users demand profiles and characteristics. In the next section, the methodology for the selection of each instrument category is described such as the needs for testing protocols described in the results section.

2.1. Transmission and distribution gas meters

Transmission and distribution gas grids differ in terms of operating flow-rate and gas pressure. Accordingly with the results shown in Ref. [18], turbine [19,20], rotary [21] and ultrasonic [22] gas meters were prevalently installed in transmission NG grids while diaphragm [23], ultrasonic and thermal mass [24] meters are prevalently installed in low-pressure distribution NG grids. Specifically, some models prevail over others for each measuring technology type. Therefore, it is necessary to prioritize the instruments to be tested.

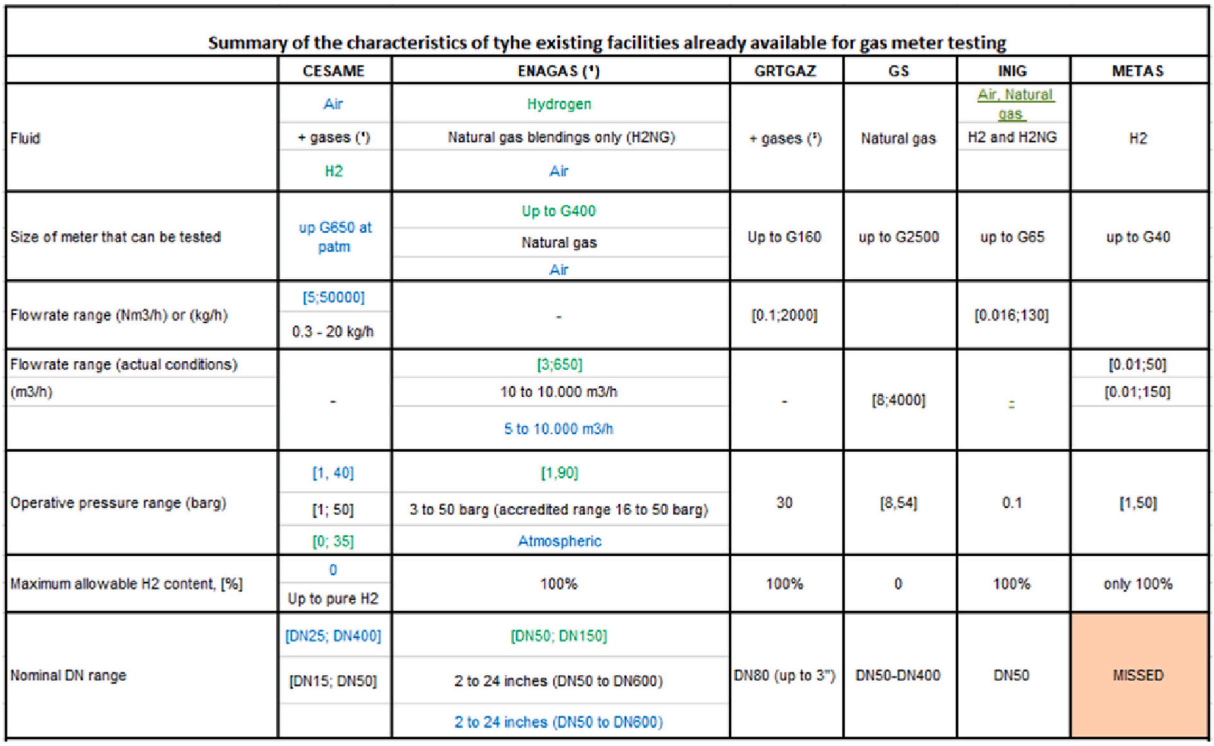
Regarding the size of the meters installed in the transmission grids, it was found that the main percentages of meters are in the range between G100 and G2500 even if some meters ≤ G65 were not declared by all the Transmission System Operators (TSOs) interviewed. Focusing on the measuring technology types, rotary gas meters are limited to size up to G650. However, in the range between G100 and G2500, turbine gas meters are the most implemented technology in the grid, followed by rotary gas meters in the lower range and ultrasonic gas meters in the upper range. Over G6500, ultrasonic gas meters are the most present technology thanks also the high turndown that the meters ensure.

The effect of H_2 on gas meters depends on the technology, and it has started to be studied in the literature [16]. However, despite several testing results being available for distribution meters, transmission gas meters are more challenging to be tested due to the high flow rate and pressure experienced in the field, that would require complex calibration facilities to obtain relevant results.

2.2. Pressure transmitters

A lot of models of pressure transmitters are installed in the gas grids of THOTH2 industrial partners. Specifically, 46 models from 13 manufacturers were identified covering three different technologies, i.e., capacitive [25], strain gauge [26], and resonant [27,28], pressure sensors as indicated in EN ISO 15970:2014 [29]. Since it would be impossible to test all the models, as a general thumb, it was agreed to prioritize the tests for at least the most relevant technologies, i.e., those devices whose market penetration is greater than a minimum threshold decided by THOTH2 industrial partners.

The effect of H_2 on pressure transmitters' metrological performance can be explained by the contact with the diaphragm. The diaphragm avoids the contact between the medium to be measured and other components within the device. However, due to the size of the molecule, H_2 permeation can occur through the diaphragm negatively impacting the accuracy of measurement. Therefore, to simulate the behaviour of the SoA measuring devices installed in the gas transmission and distribution grids, it was agreed to test the 316L stainless steel diaphragm. It should be noted that the manufacturers usually suggest that the gold-plated diaphragm be used in applications involving the presence of H_2 [30,31]. However, adopting this configuration would have been beyond the scope of the THOTH2 project since it would not allow the conclusion about any potential metrological degradation of SoA devices. Even if not



Summary of the characteristics of tyhe existing facilities already available for gas meter testing

	CESAME	ENAGAS (1)	GRTGAZ	GS	INIG	METAS
Fluid	Air + gases (1) H2	Hydrogen Natural gas blendings only (H2NG) Air	+ gases (2)	Natural gas	Air, Natural gas H2 and H2NG	H2
Size of meter that can be tested	up G650 at patm	Up to G400 Natural gas Air	Up to G160	up to G2500	up to G65	up to G40
Flowrate range (Nm3/h) or (kg/h)	[5;50000] 0.3 - 20 kg/h	-	[0.1;2000]		[0.016;130]	
Flowrate range (actual conditions) (m3/h)	-	[3;650] 10 to 10.000 m3/h 5 to 10.000 m3/h	-	[8;4000]	=	[0.01;50] [0.01;150]
Operative pressure range (barg)	[1, 40] [1; 50] [0; 35]	[1,90] 3 to 50 barg (accredited range 16 to 50 barg) Atmospheric	30	[8,54]	0.1	[1,50]
Maximum allowable H2 content, [%]	0 Up to pure H2	100%	100%	0	100%	only 100%
Nominal DN range	[DN25; DN400] [DN15; DN50]	[DN50; DN150] 2 to 24 inches (DN50 to DN600) 2 to 24 inches (DN50 to DN600)	DN80 (up to 3")	DN50-DN400	DN50	MISSED

Fig. 1. The available testing facilities in THOTH2.

Table 1
The selected transmission gas meters.

N°	Technology	Size	Calibration	Ageing
1	Rotary	G100	Air	25%vol
2		G250	Air-NG-H2NG	100%vol
3	Rotary	G100	Air	25%vol
4		G250	NG	100%vol
5	Turbine	G160	Air-H2NG	100%vol
6		G650	NG	25%vol
7		G160	Air-H2NG	100%vol
8		G650	Air-NG-H2NG	25%vol
9	Ultrasonic	DN100	H2NG-H_2	100%vol
10		DN300	NG	25%vol
11		DN100	H2NG-H_2	100%vol
12		DN300	NG	25%vol

Table 2
The selected distribution gas meters.

N°	Technology	Size	Calibration	Ageing
1	Ultrasonic	G4	NG	25%vol
2		G6		100%vol
3		G4		25%vol
4		G6		100%vol
4	Diaphragm	G4	H_2	25%vol
5		G6		100%vol
6		G10	25%vol	25%vol
7		G16		100%vol
8		G40		100%vol
9		G65		25%vol
10	Thermal mass	G4	25%vol	100%vol
11		G6		100%vol
12		G25		25%vol

shown, the range of the device is selected as the most appropriate for the measurement of typical operative pressure in NG transmission grids. In fact, since H_2 permeation increases with its partial pressure, testing at typical transmission conditions instead of distribution ones would signify testing the devices at the most severe operative conditions occurring in the NG sector.

2.3. Trace water humidity sensors

A number of devices with different working principles are commercially available on the market suitable for gas trace-water measurements: chilled mirrors, impedance sensors, quartz microbalance, optical fibre Fabry-Perot hygrometers, Tunable Diode Laser Absorption Spectrometers (TDLAS) [32–34]. A limited number of models were identified in the THOTH2 NG grids [18]. Specifically, impedance sensors are the most implemented technology followed by TDLAS.

Based on the investigation of the SoA about barriers and gaps of trace water humidity sensors in measuring H2NG mixtures or pure H_2 [16], it was agreed to focus the testing activities to investigate i) current/actual Units Under Test (UUTs) performance compared to manufacturer specifications or previous calibration certificate in N2/Air gas vector by means of a laboratory calibration; ii) drift due to normal operation conditions: the difference of the calibration results between two consecutive calibration after re-installing the UUTs in the field for at least 6 months; iii) current/actual UUTs performance compared to manufacturer specifications in NG or NGH2 blends gas vector by means of a laboratory calibration with a new primary humidity generator; iv) drift due to normal operation conditions: the difference of the calibration results between two consecutive calibrations with the new generator after re-installing the UUTs in the field for at least 6 months; v) the difference between performance between points i) and iii); vi) the difference between performance between point ii) and iv).

2.4. Leak detectors

During the SoA analysis, it was highlighted that several different types of leak detectors for monitoring NG leakages are used by Transmission and Distribution System Operators (TSOs and DSOs) [18].

As a selection criterion it was decided to test at least one device for each technology available in the market. Specifically, the tentative list of sensors to be tested includes both fixed and transportable/portable devices.

3. Results and discussion

In the following sections, the main results and the initial tasks of the THOTH2 project are reported, including the testing protocols and testing benches implemented to assess H_2 tolerances and limits of SoA measuring devices.

Fig. 2. The SGWT test bench to perform the ageing test of distribution gas meters.

3.1. Transmission and distribution gas meters

The list of transmission and distribution gas meters to be tested was developed from the analysis of the installed devices inTHOTH2 partners' grids and the assessment of the capability of the testing facilities in terms of fluids, size of meters, flowrate, operating pressures and maximum allowable H_2 content (Fig. 1). The list is shown in Tables 1 and 2 respectively for transmission and distribution gas grids. In the tables, the fluid used for calibration and for ageing is also indicated.

As shown in the tables, the testing consists of consecutive phases: initial calibration, ageing, second calibration, ageing, and final calibration.

Regarding ageing, two different mixtures have been selected, i.e., 100%vol and 25%vol. of H_2 in NG. Specifically, the ageing test will be carried out in different phases: firstly, an initial phase lasting 11 months, then a second phase lasting 5 months for some sets, and a single phase lasting 16 months for others. The ageing test will be performed at CESAME (100%vol.) and the Oil and Gas Polish Institute (INIG).

Specifically, the Stand Gas meter Test for H_2 (SGTW) at INIG will be used for the gas distribution meters' ageing test. The test bench enables to perform ageing tests of gas meters and measuring equipment using H2NG or pure H_2 in both flow and static conditions in a closed loop. A picture and the schematic of the SGTW are shown in Figs. 2 and 3.

At the end of each phase of ageing, calibrations of the meters either with air, NG, H_2 or H2NG by different partners take place. The test equipment used for this purpose consists of a reference flow measurement system equipped with the necessary measuring equipment (fluid pressure and temperature) and a test section placed in series on which the meter is mounted.

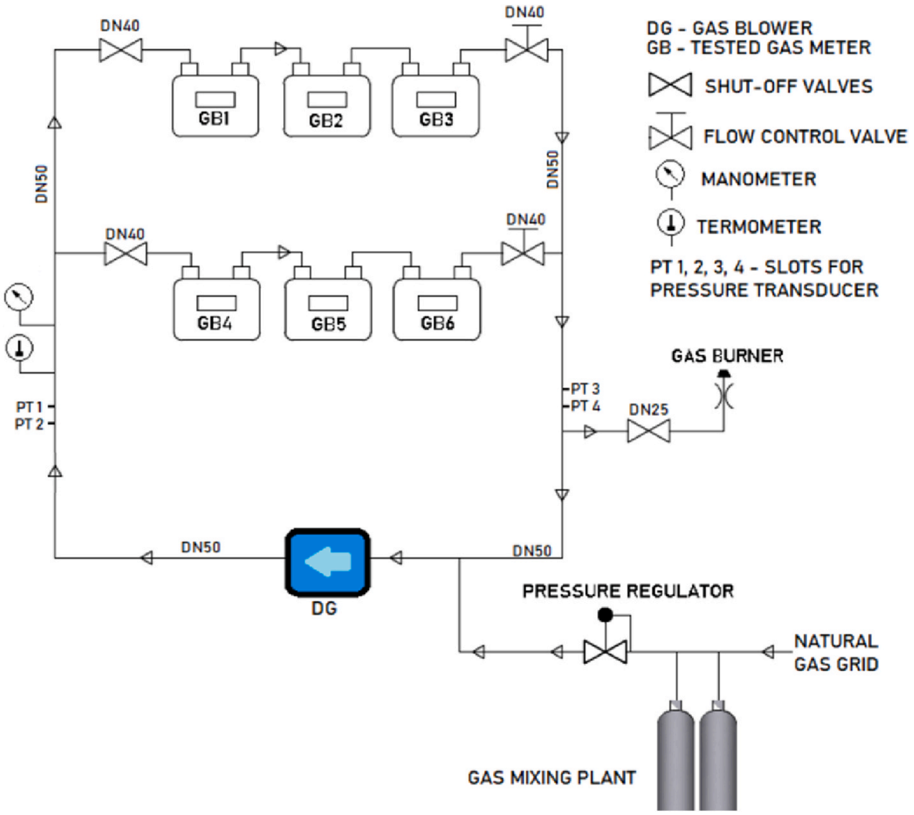


Fig. 3. The Process Flow Diagram (PFD) of the SGWT.

Table 3
The selected pressure transmitters and the main metrological performances (range and accuracy).

N°	Technology	Accuracy - Stability
1	Resonant	±0.1 % of calibrated span ±0.2 % of URL per 12 months
2	Capacitance or Piezoresistive based on application	0,04 % of calibrated span ±0.2 % of URL per 10 years
3	Piezoresistive	±0,075 % of calibrated range ≤ accuracy for 3 years
4	Piezoresistive	0,04 % of calibrated span ±0.2 % of URL for 10 years
5	Resonant	±0.055 % of calibrated span ±0.1 % of URL per 10 years
6	Resonant	±0.1 % of calibrated span ±0.1 % of URL per 12 months

3.2. *Pressure transmitters*

The list of pressure transmitters selected from the analysis of the installed devices in THOTH2 grids is shown in Table 3. In the table, the accuracy and the long-term stability declared by the manufacturers in the datasheets are reported.

The developed testing protocol consists of five phases to evaluate the effect of H2NG mixtures and H_2 on the metrological performance of SoA measuring devices: initial three-points calibration, ageing, second calibration, ageing, and final calibration. However, few examples of ageing test on pressure transmitters are shown in the literature and refer to the nuclear sector, where different stress conditions apply [35,36]. Since no technical standard defines the testing conditions to evaluate the effect of H_2 on the metrological performance of pressure transmitters, it was decided to elaborate a testing protocol starting from the existing standards that could be useful for the purpose. In the case of pressure transmitters, the definition of long-term drift (EN 61298-2:2008) [37]) and long-term stability (DIN 16086:2006-01 [38]) are considered.

Long-term drift requires that the pressure transmitter should be maintained for 30 days with an input pressure corresponding to 90 % of the span. On the other hand, the long-term stability test only indicates to maintain the pressure devices under operating conditions for one year at reference conditions. Accelerated ageing based on Arrhenius's theory by increasing testing temperature is an option to reduce the testing period. However, this approach would not exactly simulate the real-time normal ageing of a complex system such as a pressure transmitter but allows only comparative assessment of the behaviour of different devices in a shorter period [35]. Emerson developed a different accelerated operational drift test starting from the two referenced standards including temperature and pressure cycling typical of the operating conditions, and elevated temperature and pressure cycles to accelerate the drift testing [39]. A total duration of almost ten months was considered to obtain representative results.

Based on the SoA investigation, it was decided to investigate the effect of two different concentrations for ageing, i.e., 25%vol. in NG and pure H_2. Compared with the cited standards, it was decided to extend the ageing period for two periods of four months, maintaining the gas at a pressure of 65 barg, i.e., approximately the operating value in gas transmission grids downstream the compression stations. Compared to the in-house protocol developed by Emerson, it was decided not to operate an accelerated ageing by increasing the temperature because the purpose of the test would not be to compare different models but to simulate real-time normal ageing. Since gas grids are usually buried, testing the measuring devices at a temperature of $\pm 5\ ^\circ\mathrm{C}$ with respect to the desired set point would be representative of the experienced conditions on the field.

From an operating point of view, ageing tests will be performed at CESAME-LNE (pure H_2) and at INIG (H2NG mixture) laboratories. Several precautions have to be taken to ensure the success of the ageing

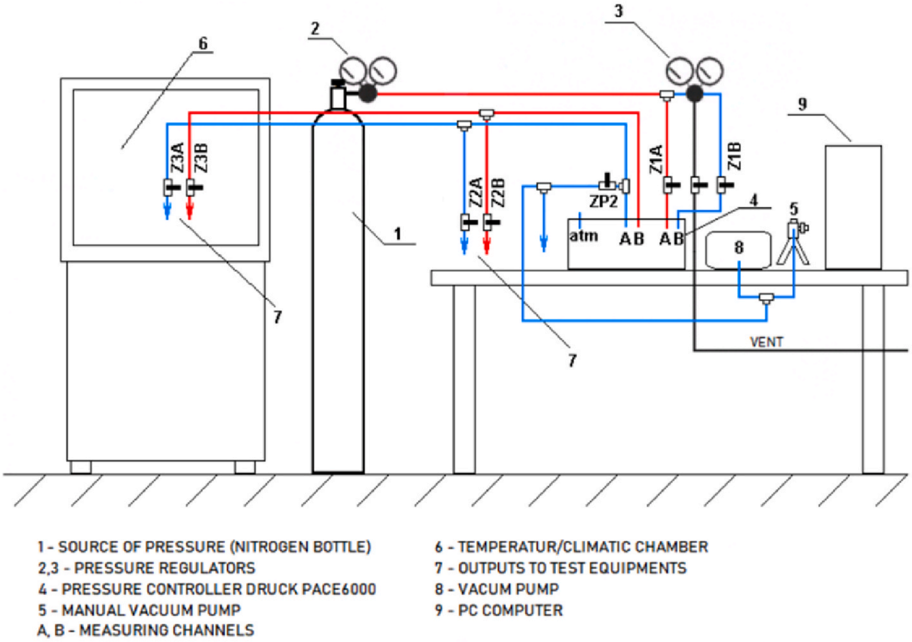


Fig. 4. The Process Flow Diagram (PFD) of the calibration facility operated at INIG for the calibration of the pressure transmitters.

Table 4
Selected trace water humidity sensors and their metrological performances (range and accuracy).

N°	Technology	Range - Accuracy
1	TDLAS	Range: up to 6000 ppmv Accuracy: ±2 ppmv plus ±2 % o.r.
2	Ceramic metal-oxide	Range: [-100; 20] °C; 10 ppbv-23000 ppmv Accuracy: ±1 °C (>-60 °C); ±10 % o.r.; ±2 °C; ± 20 % o.r. (<−60 °C)
3	TDLAS	Range: 0–1000 ppmv Accuracy: ±1 % o.r. (>100 ppmv); ± 1 ppmv (<100 ppmv)
4	Ceramic metal-oxide	Range: [-100; 20] °C Accuracy: ±1 °C (>-60 °C), ±2 °C (<-60 °C)
5	Aluminum oxide	Range: [-110; 20] °C Accuracy: ±1 °C (>−60 °C) ±2 °C (<−60 °C)

testing. First of all, since several devices could be tested simultaneously by the connection to a common manifold, attention has to be given to maintaining the testing pressure at the set point value to counteract any release occurring, for example, from connection fittings. Second, flushing has to be performed to avoid the persistence of air bubbles in the test bench that would prevent contact with the diaphragm and reduce the partial pressure of the testing gas.

Once the ageing is completed, the devices will be calibrated in accordance with the relevant technical standards at the INIG facility, that is part of the International Laboratory Accreditation Cooperation Mutual Recognition Arrangement (ILAC MRA). The Process Flow Diagram of the calibration facility operated at INIG is shown in Fig. 4. Nitrogen is used as fluid during the calibration. Nitrogen gas is stored into the bottles (1) connected to the device under test. Pressure regulators (2) are installed at the exit of the bottle to ensure a stable pressure upstream of the measuring device. Furthermore, a pressure calibrator (4) is installed to ensure a stable and accurate input pressure to the devices to be calibrated. The output signal for the converters, i.e., a voltage or current signal, is measured by a reference multimeter, or a HART signal read by a device using the HART communication protocol.

3.3. *Trace water humidity sensors*

Based on the results of the survey performed during the project, the measuring devices shown in Table 4 were selected. As shown, the technologies selected are TDLAS, ceramic metal-oxide and aluminium oxide and are characterized by similar metrological performance in terms of measuring range and accuracy. The term "o.r." denotes operating range for clarity.

Six phases were identified for testing the water trace humidity sensors. The first phase investigates the initial performances of the devices under test (DUTs) and the measurement of the short-term stability. For this purpose, DUTs calibration will be performed as common practice and compared against the current Primary Humidity Standards in air or N_2 from 1 bar to the maximum pressure allowed by the selected device unit (SDU) or the calibration facility. In the second phase, the DUTs will be re-installed in the field for eight months, being in contact with NG and/or H2NG mixtures. In the third phase, DUTs will be re-calibrated in the laboratory to investigate possible changes due to H_2 with respect to the initial calibration. In the fourth phase, the selected DUTs will undergo a revised-practice calibration in the laboratory. Specifically, the revised-practice will simulate an on-site calibration by using the new deployable calibration system in H_2 at a pressure from 1 bar up to 55 bar. Once calibrated according to the revised-practice, the DUTs will be installed again in the field for five months. Last, in the sixth phase, the DUTs will be calibrated again with the newly developed practice to investigate possible changes due to H_2, aiming to assess possible differences in water condensation formation and to compare the calibration in gas against H_2.

Testing activities will be performed at the Italian National Metrology Institute, i.e. INRIM. The expertise, competence and facilities shared by INRIM include the development of primary standards and measurement techniques for humidity in gases, the measurement of thermo-physical properties of real gas mixtures, as well as the measurement of surface and air temperature. The humidity laboratory shares a broad range of calibration and testing facilities to provide measurement traceability to sensors and analysers for trace water measurements in different gas matrices including energy-relevant gases. The INRIM-01 and INRIM-02 primary humidity generators are recirculating-type generators that operate according to the single-pressure and single-temperature

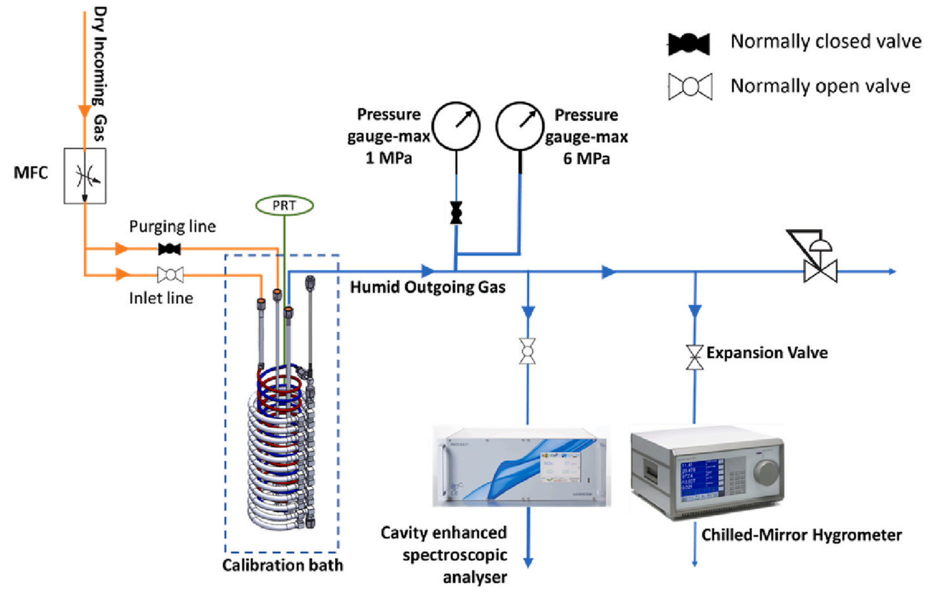


Fig. 5. Process flow diagram of the moist-H_2 transportable precision humidity generator (TPHG) developed at INRIM.

Table 5
The selected leak detector sensors to be tested.

N°	Technology
1	Catalytic sensor
2	Infrared + Catalytic sensor
3	Catalytic + electrochemical sensors
4	Infrared sensor
5	Semiconductor CH_4 0–100 % LEL, 1 % Catalytic Bead, CH_4 0–100 % Volume, 1 % Thermal Conductivity
6	Catalytic sensor
7	Infrared sensor
8	Semiconductor + catalytic + thermal conductivity sensors
9	Semiconductor + catalytic + thermal conductivity sensors
10	Infrared sensors

principle. They cover the dew/frost point temperature range from −85 °C to 95 °C. In both systems, the working pressure is kept constant to better than 0.05 % for any value between 1000 hPa and 1200 hPa, typically at 1050 hPa, by using an electronic pressure controller. The INRIM-03 Mark 1 humidity generator is a single-pressure, single-temperature generator that operates by saturating a nitrogen flow gas over an isothermal, uniform, ice layer in the frost-point temperature range between −100 °C and −20 °C and in the pressure range from 200 hPa to 0.68 MPa.

For the revised practice an innovative test bench designed within the EU Metrology Partnership project 21GRD05 Met4H2 will be used [14]. The system whose Process Flow Diagram (PFD) is illustrated in Fig. 5, consists of a transportable, single-pass, precision humidity generator (TPHG) to provide state-of-the-art onsite traceability to trace water measurements in hydrogen. The moist-H_2 TPHG is a water vapour saturation-based generator, designed at INRIM capable of generating a moist hydrogen stream with an amount of water fraction between 0.5 μmol/mol and 50 μmol/mol at any pressure between 0.2 MPa and 5.5 MPa or, equivalently, a stream with a pressure dew-point in the range between −55 °C and −10 °C. Further to its operation as a moist H_2 generator, the system has been designed for flexible multi-gas, multi-pressure operation in order to be easily retrofitted to enable trace water sensors testing and calibration in CH_4/H_2 gas blends.

3.4. *Leak detectors*

A tentative list of sensors to be tested were obtained by the THOTH2 project as shown in Table 5. Even not indicated in the table, additionally, ultrasonic gas leak detectors could be added to the list as a representative device to be tested for evaluating the performance of acoustic-based sensors in the presence of H_2/NG blends. Only the H_2 influence on device limit of detection will be evaluated.

To date, the standards that currently regulate performance requirements and the related tests, as well as selection procedure, installation use and maintenance of gas sensors for monitoring explosive atmospheres are IEC 60079-29-1:2016 [40] and IEC 60079-29-2:2015 [41]. Furthermore, fixed ultrasonic gas leak detectors are regulated by the EN 50724 standard [42]. The existing standards provide comprehensive guidelines for testing and selecting sensors suitable for detecting explosive atmospheres in common applications. However, the use of H_2 or H2NG mixtures introduces new variables and challenges to properly assess sensor performance for monitoring potential gas leakages at various H_2 concentrations and component ratios.

The developed testing protocol will consist in the measurement of i) the calibration curve, ii) stability, iii) alarm set points, iv) time of response, v) high gas concentration operation above the measuring range and vi) poisons.

The testing of leak detectors will be performed at Fondazione Bruno Kessler (FBK) and INIG facilities. FBK has a long-term experience on the development of flow sensors and solid-state gas sensors, specifically chemoresistive gas sensors. In order to be able to characterize, calibrate and validate the gas sensors internally produced, a dedicated lab has been set up, i.e., the Gas Qualification Laboratory (Laboratorio Qualifica Gas). The laboratory has been designed to provide tools, systems and facilities useful for the development, integration and testing of gas sensing devices and flow sensors. The Gas Qualification Laboratory is a 5 × 6 m^2 laboratory. Currently, the laboratory hosts four gas test benches:

- MKS gas test bench, equipped with six MKS mass flow controllers, six electrovalves, and a multi-channel flow ratio/pressure controller model 647C manufactured by MKS;
- Brooks gas test bench, equipped with five Brooks mass flow controllers, five electrovalves and a multi-channel flow ratio/pressure controller model 0260 manufactured by Brooks;
- Alicat gas test bench, equipped with 3 Alicat mass flow controllers and a multi-channel flow ratio/pressure controller manufactured by Alicat;

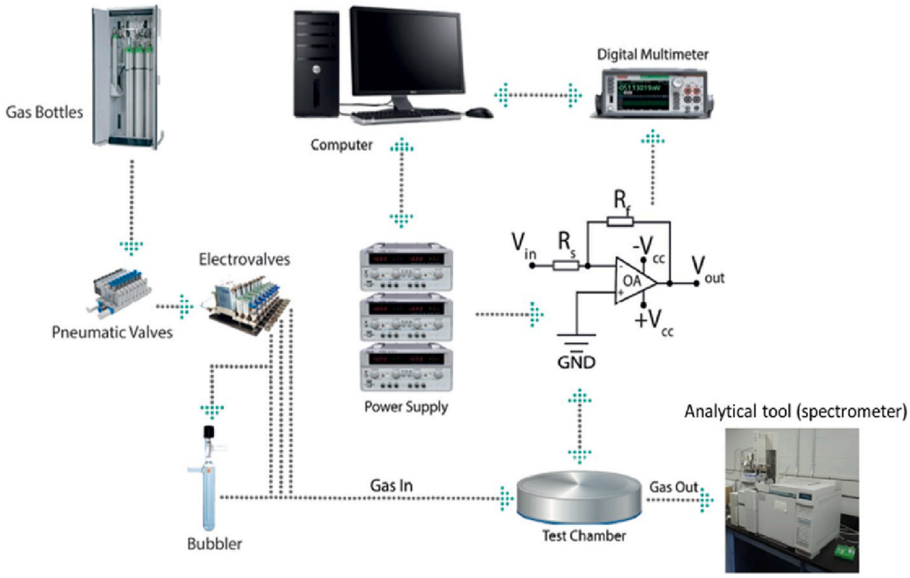


Fig. 6. Process Flow Diagram of the test bench. Reuse in a journal under STM guidelines [43]

- A portable gas test bench, placed on a wheeled bench, and equipped with calibrated four mass flow controllers from manufacturers, four electrovalves and a customized multi-channel flow ratio/pressure controller.

A general scheme of the test benches at FBK is shown in Figure. All four gas test benches can be driven using a dedicated communication and data acquisition application, developed using LABVIEW software, which allows to communicate and to drive mass flow controllers, including setting, saving and uploading automatic gas flow injections, and storing, in real time, actual flow data related to the gas test benches. In addition, four different gas chambers equipped with related read-out electronic boards are available. In particular, the gas chambers have been designed for hosting and testing solid state gas sensors, while the electronic read-out can be used to collect gas sensor data, as well as to communicate and set the working parameters of the devices investigated. The gas chambers are placed in a climate chamber, in order to make the tests at different temperatures and relative humidity. Outside the laboratory is present a gas box, containing seven double-body pressure reducers which can host, simultaneously, seven different gas bottles. The gas box is equipped with electropolished stainless steel tubes, dedicated to the transport of the gas mixtures.

The GU_84 test bench for leakage detection devices will be operated at INIG. The primary function of the testing bench is to generate specified gas volume flow rates. This task is achieved through the MCR flow controller - 50 l/min - D - 5M – 5IN - RS485 MODBUS - HC – GAS. The flow controller enables the generation of prescribed emission levels of NG, H_2, and their mixtures. Additionally, the test bench is equipped with a set of devices to simulate atmospheric conditions that may interfere with measurements:

- Active background heating mat: This mat allows for heating the background to a temperature 10 °C above ambient, simulating conditions where the background temperature is elevated.
- Three Monsoon EXO TERRA misting nozzles: These nozzles enable adjustments to the test bench's operating parameters, including air humidity and misting to simulate varying environmental conditions.
- Piezoelectric buzzer: This buzzer generates noise at a frequency of 3.7 kHz ± 0.5 kHz with a sound level of approximately 82 dB, simulating ambient noise conditions.

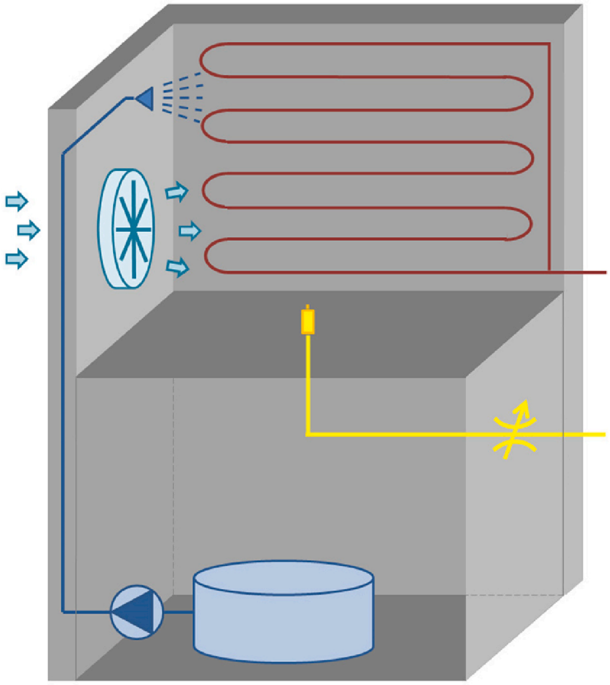


Fig. 7. Scheme of the test bench for leakage detection devices.

- AABCOOLING Super Silent Fan 12 Pro: This fan serves as a wind generator, capable of producing wind speeds of up to 5 m/s to simulate air movement (see Fig. 6).

A drawing of the facility is reported in Fig. 7.

4. Conclusions

An extensive plan of testing activities has been established to be performed during the THOTH2 project. These activities aim to validate the developed protocols and contribute to the definition of the limits and tolerances of SoA measuring devices installed in NG sectors, including gas meters, pressure transmitters, trace water humidity sensors, and leak detectors.

For this purpose, starting from analyzing the effectively installed measuring devices and the availability of a testing bench in the consortium, the THOTH2 project designed the protocols and the procedures to be followed in the experimental activities.

Based on the experimental results, the THOTH2 project will contribute to the roadmap toward a sustainable energy future where H2NG mixtures or pure H_2 could be transported along long distances by the existing NG infrastructures.

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References

[1] I. Staffell, D. Scamman, A. Velazquez Abad, P. Balcombe, P.E. Dodds, The role of hydrogen and fuel cells in the global energy system, Energy Environ. Sci. 12 (2019) 463–491, https://doi.org/10.1039/c8ee01157e.
[2] A. Kova, M. Paranos, D. Marciu, Hydrogen in energy transition: a review, Int. J. Hydrogen Energy 46 (2020) 10016–10035, https://doi.org/10.1016/j.ijhydene.2020.11.256.
[3] F. Dawood, M. Anda, G.M. Shafiullah, Hydrogen production for energy: an overview, Int. J. Hydrogen Energy 45 (2019) 3847–3869, https://doi.org/10.1016/j.ijhydene.2019.12.059.
[4] G. Han, Y. Kwon, J. Bae Kim, S. Lee, J. Bae, Development of a high-energy-density portable/mobile hydrogen energy storage system incorporating an electrolyzer, a metal hydride and a fuel cell, Appl. Energy 259 (2020) 114175, https://doi.org/10.1016/j.apenergy.2019.114175.
[5] M. Mcpherson, N. Johnson, M. Strubegger, The role of electricity storage and hydrogen technologies in enabling global low-carbon energy transitions, Appl. Energy 216 (2018) 649–661, https://doi.org/10.1016/j.apenergy.2018.02.110.
[6] G. Lo Basso, B. Nastasi, D.A. Garcia, F. Cumo, How to handle the Hydrogen enriched Natural Gas blends in combustion efficiency measurement procedure of conventional and condensing boilers, Energy 123 (2017) 615–636, https://doi.org/10.1016/j.energy.2017.02.042.
[7] T. Amirthan, M. Perera, The role of storage systems in hydrogen economy: a review, J. Nat. Gas Sci. Eng. 108 (2022) 104843, https://doi.org/10.1016/j.jngse.2022.104843.
[8] R. Moradi, K.M. Groth, Hydrogen storage and delivery: review of the state of the art technologies and risk and reliability analysis, Int. J. Hydrogen Energy 44 (2019) 12254–12269, https://doi.org/10.1016/j.ijhydene.2019.03.041.
[9] H. Barthelemy, M. Weber, F. Barbier, Hydrogen storage: recent improvements and industrial perspectives, Int. J. Hydrogen Energy 42 (2017) 7254–7262, https://doi.org/10.1016/j.ijhydene.2016.03.178.
[10] J.B. Cristello, J.M. Yang, R. Hugo, Y. Lee, S.S. Park, Feasibility analysis of blending hydrogen into natural gas networks, Int. J. Hydrogen Energy 48 (2023) 17605–17629, https://doi.org/10.1016/j.ijhydene.2023.01.156.
[11] A. Witkowski, A. Rusin, M. Majkut, K. Stolecka, Analysis of compression and transport of the methane/hydrogen mixture in existing natural gas pipelines, Int. J. Pres. Ves. Pip. 166 (Sep. 2018) 24–34, https://doi.org/10.1016/j.ijpvp.2018.08.002.
[12] M.W. Melaina, O. Antonia, M. Penev, Blending hydrogen into natural gas pipeline networks: a review of key issues, Available: http://www.osti.gov/bridge, 2013.
[13] NewGasMet: The Project. [Online]. Available: https://newgasmet.eu/the-project.
[14] Met4H2, Metrology for the hydrogen supply chain. [Online]. Available: https://met4h2.eu/.
[15] THOTH2, Novel meTHOds of Testing for measurement of natural gas and H2 mixtures. [Online]. Available: https://thoth2.eu/news-and-publications/first-thoth2-advisory-board/.
[16] A. Dudek, P. Kulaga, M. Gajec, J. Holewa-Rataj, L. Maciej, Barriers and gaps of SoA NG transmission and distribution measuring devices in H2NG flows. https://doi.org/10.5281/zenodo.1081436, 2024.
[17] P. Gislon, N. Cerone, V. Cigolotti, A. Guzzini, M. Pellegrini, Hydrogen blending effect on fiscal and metrological instrumentation: a review, Int. J. Hydrogen Energy (2024), https://doi.org/10.1016/j.ijhydene.2024.02.227 (in press).
[18] M. Pellegrini, M. Gentilini, R. Manieri, C. Saccani, J. Modrego Neila, SoA of measuring devices installed in NG transmission and distribution networks. https://doi.org/10.5281/zenodo.10814350, 2024.
[19] R.C. Baker, Turbine and related flowmeters: I. Industrial practice, Flow Meas. Instrum. 2 (1991) 147–161.
[20] R.C. Baker, Turbine flowmeters: II. Theoretical and experimental published information, Flow Meas. Instrum. 4 (1993) 123–144.
[21] R.B.J. Richards, Rotary Piston Gas Meter, 1999. CA2296985A1.
[22] J.G. Drenthen, G. De Boer, The manufacturing of ultrasonic gas flow meters, Flow Meas. Instrum. (2001). Available, www.elsevier.com/locate/flowmeasinst.
[23] F. Cascetta, P. Vigo, The future domestic gas meter: review of current developments, Measurement 13 (1994) 129–145, https://doi.org/10.1016/0263-2241(94)90006-X.
[24] M. Hohenstatt, A thermal mass flow meter for process control, in: IFAC 10th Triennal World Congress, 1987.
[25] R.B. Mishra, N. El-Atab, A.M. Hussain, M.M. Hussain, Recent progress on flexible capacitive pressure sensors: from design and materials to applications, Advan. Mater. Technol. 6 (4) (Apr. 01, 2021), https://doi.org/10.1002/admt.202001023. John Wiley and Sons Inc.
[26] S. Boyn, Piezoresistive pressure measurement technology, Available: https://download.keller-druck.com/api/download/TcyEX9Ug2P8gw36uhvXAZc/en/2019-03.pdf, 2019.
[27] T. Samejima, Y. Suzuki, N. Hamamatsu, H. Yokouchi, T. Yoshida, High-sensitivity silicon resonant strain sensor, Yokogawa Tech. Rep. 60 (1) (2017).
[28] J. Bryzek, J.R. Mallon, Silicon resonant pressure sensors-A market perspective, Sensor. Mater. 9 (8) (1997) 473–500.
[29] EN ISO 15970, Natural Gas - Measurement of Properties - Volumetric Properties: Density, Pressure, Temperature and Compression Factor, 2014.
[30] Emerson, Material Selection and Compatibility Considerations for Rosemount TM Pressure Transmitters, 2018.
[31] ABB, Pressure measurement corrosion and material selection guide. Available: www.abb.com/measurement.
[32] G. McKeogh, Moisture Measurement Technologies for Natural Gas, 2020.
[33] T.V. Løkken, Comparison of Hygrometers for Monitoring of Water Vapour in Natural Gas, Norwegian University of Science and Technology, 2015. PhD Thesis.
[34] T.V. Løkken, Water vapour measurements in natural gas in the presence of ethylene glycol, J. Nat. Gas Sci. Eng. 12 (May 2013) 13–21, https://doi.org/10.1016/j.jngse.2013.01.002.
[35] H.M. Hashemian, K.M. Petersen, R.E. Fain, J.J. Gingrich, Effect of Aging on Response Time of Nuclear Plant Pressure Sensors, 1989.
[36] H.M. Hashemian, Aging Characteristics of Nuclear Plant RTDs and Pressure Transmitters, the 4th International Topic Meeting on Nuclear Thermal Hydraulics Operations and Safety, 6-8 Apr. 1994. Taipei, Taiwan.
[37] EN 61298-2, Process Measurement and Control Devices - General Methods and Procedures for Evaluating Performance - Part 2: Tests under Reference Conditions, BSI, 2008.
[38] DIN 16086:2006-01, Electrical Pressure Measuring Instruments - Pressure Transmitters, Pressure Measuring Instruments - Concepts, Specifications on Data Sheets, 2006.
[39] L. Buggenhout, What Is Long Term Stability of Pressure Sensors, 2023.
[40] IEC 60079-29-1:2016, Explosive Atmospheres - Part 29-1: Gas Detectors - Performance Requirements of Detectors for Flammable Gases, 2016.
[41] IEC 60079-29-2:2015, Gas Detectors - Selection, Installation, Use and Maintenance of Detectors for Flammable Gases and Oxygen, 2015.
[42] EN 50724:2023, Fixed Ultrasonic Gas Leak Detectors (UGLD) - General Requirements and Test Methods, 2023.
[43] M. Valt, B. Fabbri, A. Gaiardo, S. Gherardi, D. Casotti, G. Cruciani, G. Pepponi, L. Vanzetti, E. Iacob, C. Malagù, Aza-crown-ether functionalized graphene oxide for gas sensing and cation trapping applications, Mater. Res. Expr. 6 (2019) 075603, https://doi.org/10.1088/2053-1591/ab11fb.

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