Hydrogen in natural gas infrastructure: techno-economic assessment of repurposing existing grids

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Abstract: Renewable hydrogen (H_2) blending and H_2 transport in existing natural gas (NG) grids are expected to support energy decarbonisation while reducing delivery costs. However, several regulatory (like ATEX Directives) and technological issues concerning the existing infrastructure still need to be addressed. Among the technological barriers, measurement performance is paramount in NG transmission and distribution networks for fiscal, process, monitoring, and safety purposes. Measuring device categories include gas meters, pressure and temperature transmitters, gas chromatographs, trace water humidity sensors, and leak detectors. Researchers involved in the projects "Novel methods of testing for measurement of natural gas and hydrogen mixtures" (THOTH2) and the PNRR "Network for Energy Sustainable Transition" (NEST) are collaborating to identify H_2 limits and thresholds for State-of-the-Art (SoA) measuring devices through experimental tests. The paper presents actual data about the devices installed in the Italian NG grids, allowing the definition of the current SoA. The analysis helps estimate the effort and costs necessary to adapt the existing gas network by replacing devices unsuitable for measuring hydrogen and natural gas (H2NG) mixtures. For this reason, the effect of different hydrogen thresholds related to the maintenance of the measurement performance is also presented.

Keywords: Hydrogen; Natural gas and hydrogen mixtures; Hydrogen Blending; Gas measuring devices and sensors; Gas transportation and distribution

1. Introduction

Recently, an interest in studying solutions for gradually reducing fossil fuels' utilisation has widely spread. Decarbonisation is becoming unavoidable in the gas transmission and distribution sectors, and it is necessary to achieve climate neutrality in Europe by 2050. Due to the strategic role of the existing gas infrastructures in the European energy system, the possibility of adapting them to convey renewable hydrogen has been investigated by several authors (Bellocchi et al., 2023; Cristello et al., 2023; Galyas et al., 2023; Gas Infrastructure Europe, 2021; Gislon et al., 2024; Hanto et al., 2023; Mahajan et al., 2022). Although the literature agrees that renewable H_2 could be an option for the energy transition in hard-to-abate sectors (steelmaking, refineries, chemical, pulp and paper, etc.), as assessed by demonstrators and research studies (Mati et al., 2023; Nurdiawati and Urban, 2022; Ramachandran and Menont, 1998; Rechberger et al., 2020), several techno-economic challenges still hinder the deployment in large-scale market applications such as, production cost, storage size, authorisation procedures.

Producing renewable H_2 in remote areas and transporting it to the final end-users is another option to increase its competitiveness compared to traditional fossil energy sources. For example, Cavana & Leone investigated the production of renewable H_2 in North Africa and its transportation to Italy through the existing Greenstream in four H2 blending scenarios (Cavana and Leone, 2021). Since lower production costs could be achieved with this method, other authors evaluated the feasibility of transporting renewable H_2 through the existing gas networks over long distances (Cardinale, 2023; Timmerberg and Kaltschmitt, 2019). Even if, in the long term, the construction of a pure H2 network more than 40,000 km long is planned, i.e., the H2 backbone (Sagdur et al., 2023), re-using the existing grids is one of the most promising ways to transport large amounts of gaseous H_2 for long distances. Regardless of whether a pipeline appears to be the most worthwhile way of hydrogen delivery, it can be considered the option with a lower likelihood of accidents and exposure to humans (Aghakhani et al., 2023). Pipeline delivery mode also has the lowest greenhouse gas (GHG) emission per kg of H_2 delivered. Therefore, the choice to repurpose the existing gas grid would have a twofold perspective: the evolution of the existing asset creates new business opportunities for operators and supports energetic sustainability.

However, the discussion about the H_2 concentration limits in grids designed for natural gas is still open between gas Transmission System Operators (TSOs). Among the gas TSOs, there are two philosophies: using existing networks to transport a mixture of hydrogen and natural gas or directly transporting pure H_2. In both cases, knowing the threshold beyond which metrological and safety performances of the measuring devices are not guaranteed would be paramount to control H2 injection into the grid and identify the components to be replaced in the case of pipeline repurposing. However, many different categories of components are installed along the network, requiring specific investigation instead of a generic approach, and the matter is still at the research level. The investigation is focused on providing answers on the compatibility of materials (San Marchi et al., 2014; Wang et al., 2022), the effects on specific components such as valves and welds (Jia et al., 2023) and safety aspects including stratification in vertical pipes (Liu et al., 2023), the estimation of leakage from buried pipelines (Wang et al., 2023), or a more general overview concerning risks in the transportation of H_2 blend (Tian and Pei, 2023).

To address the issue of the effects on the metrological performance of measuring instruments, these devices must satisfy the requirements indicated by the Measuring Instruments Directive, i.e. the MID (European Commission, 2014), to be used for fiscal purposes. EU-funded projects like DeCarb, Met4H2, and NewGasMet have already shown preliminary results. Still, few experimental data are available for measuring devices installed in gas transmission grids where high-pressure and high-flowrate occur. To solve this gap, the EU co-founded THOTH2 project focuses on measuring devices by trying to i) develop new testing protocols to experimentally assess the H_2 limits in State-of-the-Art (SoA) NG measuring devices, ii) provide suggestions to technical committees involved in standardisation roadmap, iii) suggest targets to technological research in new measuring devices starting from existing experience and know-how about the performances of SoA devices. To ensure rigorous analysis, the THOTH2 consortium includes four EU TSOs covering almost 40% of the total EU transmission grid, research institutes and national metrological institutes (NMIs). A focus on the Italian NG infrastructure is instead performed within the PNRR-NEST project, considering the national normative framework.

The paper aims to perform a preliminary analysis on the impact of H_2 and H2NG mixtures on the measuring devices currently installed in Italian NG grids. Because of the lack of primary experimental measurements, the considerations on H_2 impact are based on the available information in the literature and on the contacts maintained with the manufacturers. For this purpose, the paper is structured as follow. Section 2 presents the structure of the Italian gas transmission network. SoA of meters and quality analysers is discussed in Section 3, describing their operating principles. Section 4 provides an overview of the measurement devices installed in Italy. The results presented were achieved during the development of WP1 of the THOTH2 project, where the results of all measurement technologies related to European gas transmission and distribution networks are collected. Section 5 illustrates the fundamentals of the methodology for estimating the investment needed to convert the existing network. Finally, the conclusions of the work are provided.

2. Quantity and quality measurements in transmission natural gas networks

In Italy, the gas transmission operator manages the infrastructure from the entry points to the delivery points. A fundamental practice for network control is measurement, primarily aimed at ensuring the best management of commercial transportation transactions. The measurement process involves a complex set of technical activities related to the collection, processing, validation, and availability of data collected at the measurement facilities. These activities aim to obtain energy data from quantity and quality measurements. Therefore, the primary measurement instruments in this process relate to volume and quality measurements, precisely meters and quality analysers, which are essentially gas chromatographs. In addition to these two instruments, the gas network is equipped with several other measurement devices used for fiscal, process, and safety purposes. The equipment includes volume converters, pressure and temperature transmitters, trace water humidity sensors, and leak detectors (Pellegrini et al., 2024).

The gas measurement activity at the delivery points (PdR, *Punti di Riconsegna*) is carried out at facilities called ReMi, which the end customers own. The measurement unit has a structure that handles the acquisition and validation of flow rate data produced by these facilities, verifies the compliance of plant modifications, and oversees the updating of quality data in the flow computers. Specific rules for energy calculation are outlined in Del. 512/R/2021/Gas (ARERA, 2021) and in the technical standard UNI 9167-3:2020 (UNI, 2020).

Gas quality measurement aims to determine the parameters necessary for processing the energy quantities of the gas injected and withdrawn from the transmission network. To this end, it is required to know the gas composition, which is determined through gas chromatography, and calculate the physical parameters of natural gas, including the Higher Heating Value (HHV) and the compressibility factor. Gas quality measurement is carried out at the entry and exit points of the transmission network. Typical entry points are import points, LNG plants, gas fields, storage withdrawals, and interconnections with other transmission networks. Regarding the exit points, the transmission network is divided into specific zones called *Aree Omogenee di Prelievo* (AOP). The operator introduced the AOPs to optimise and monitor natural gas distribution since the grid transports gas from different sources, and gas analysis equipment is not present at all delivery points. These boundaries are identified at specific points in the network, such as injection facilities, network nodes, and gas delivery points, and they are updated regularly (SNAM, 2023). For each AOP, the HHV value of the transiting gas is continuously determined through a gas chromatograph.

3. State-of-the-Art of measurement devices in natural gas networks

3.1 Gas meters

Many commercial devices are available on the market to measure NG flow rates. The first classification is between volume totalisers and flow rate meters. Volume totalisers measure the flow rate by isolating the fluid in a closed chamber with a known volume (e.g., rotary piston gas meters and diaphragm gas meters) or by counting the number of electrical or mechanical pulses generated by the passage of the fluid (e.g., turbine gas meters). Flow rate meters, on the other hand, measure the volumetric or mass flow rate by measuring other fluid properties and applying well-known physical correlations. The main metrological characteristics are shown in Table 1, while the primary barriers against H_2 for each instrument are provided in (Dudek et al., 2024). The measurement principles are presented below.

3.1.1 Turbine gas meters

Turbine gas meters consist of a bladed rotor that rotates due to the flow in the measuring chamber (Baker, 1993, 1991). The fluid is directed through an inlet straightener to the rotor, where it encounters the blades, triggering the rotation: greater velocity, pressure, or both result in better metrological performance due to increased driving force. The rotor movement is transferred to the shaft, supported by lubricated bearings within the measurement chamber, and to the counting mechanism (totaliser unit) to measure the gas volume. As Baker (1991) reported, the rotor design is conceived to minimise disturbances to the incoming flow. In the ideal case, the flow rate is proportional to the number of pulses, and the relation is indicated by a so-called meter constant, usually expressed in pulses per unit of volume by the manufacturers. However, drag forces on the blades, the hub, the faces of the rotor, and the tip, as well as friction losses on the bearings, reduce linearity (Facouhi, 1977).

3.1.2 Rotary gas meters

Rotary piston gas meters have been well-known in the gas sector since 1920. The most common configuration includes two counter-rotating figure "8" shaped rotors called impellers. The pressure difference between the inlet and outlet creates a force that rotates the rotors, which are geared through external synchronisation gears. The measuring operation can be divided into four phases. Starting from the inlet, a known gas volume enters the meter and is isolated between the lobes and the meter's body. In the second step, the gas volume starts to move downstream following the rotation of the rotor. At the same time, the second rotor begins to trap another gas volume. The gas volume is discharged in the third and fourth steps, and another volume is entrapped to start the cycle again. Therefore, four defined volumes of gas are moved for each complete rotation. Additionally, gas leakage occurs through the clearance paths between the impellers and the main body (Schwarz, 2018).

3.1.3 Ultrasonic gas meters

Ultrasonic gas meters use two measuring methods to calculate the volumetric flow rate: time difference measurement (transit time) and the Doppler method. In the first case, the measure is time, while in the second, it is the change in frequency. In the first configuration, the gas velocity is calculated by measuring the difference in transit times of ultrasonic pulses emitted by transducers on the meter. When no flow is present, the time difference is zero since the transit time of the pulses is inversely proportional to the speed of sound in the fluid. In the flow case, the ultrasonic pulses are accelerated when propagating in the same direction as the gas flow. Conversely, they decelerate when moving in the opposite direction. Specifically, the greater the gas velocity, the higher the time difference (Dell'isola et al., 1997).

3.1.4 Diaphragm gas meters

Diaphragm gas meters are usually implemented in the gas distribution sector, as their installation in gas transmission grids is limited to local process purposes, e.g., the gas supply to process applications (Cascetta and Vigo, 1994). Diaphragm gas meters measure the volumetric flow rate by passing the fluid through chambers with deformable walls. The principle involves isolating, during each single measurement, a known volume of gas in two measuring chambers. The size of each one coincides with the measurement volume and is equal to a quarter of the cyclic volume. Therefore, a fixed gas volume is displaced for each diaphragm stroke. The measurement consists of both the continuous repetition of the operations of filling and emptying the gas from the chambers and considering the number of times this cyclic operation is performed. However, in field conditions, the meters' performance often deteriorates because of the abrasion of the moving parts and material ageing over time.

3.1.5 Thermal mass meters

Thermal mass gas meters monitor the cooling effect of the moving fluid on a heated element. The electric power supplied to maintain the sensitive component at a constant temperature, or the temperature difference from the set-point value, is proportional to the gas mass flow rate. The fluid inside the measuring section passes through two temperature transducers. One of the two resistance thermometers is used as a standard temperature-sensing device and monitors the current process values. The other acts as a heater (Jaworski and Dudek, 2020). The heater can operate in two modes, i.e., constant current anemometer (CCA) and constant temperature anemometer (CTA). In the CCA configuration, the heater is maintained at a constant differential temperature higher than the process temperature by varying the electrical energy consumed by the sensor. The higher the mass flow, the greater the cooling effect and the energy required to maintain the temperature difference. The mass flow rate is calculated by measuring the electric current supplied to the heater. The heater is powered with a constant electric current in CTA devices, while the temperature difference is measured proportionally to the flow rate.

3.1.6 Coriolis gas meters

Coriolis gas meters measure mass flow rate. The first use of Coriolis flow meters in the natural gas sector for custody transfer applications dates back to 1995. Ten years later, the calibration of CMF300 Coriolis meters produced by Micro Motion showed promising results (Riezebos et al., 2004). Coriolis meters have proven to be a reliable method for measuring natural gas flow rates (Buttler, 2016). The operation of Coriolis meters is based on the Coriolis force. The meter can be designed with one or multiple balanced meter tubes interconnected at the ends. The tube system, also known as the sensor, utilises a centrally positioned electromechanical setup to induce vibrations in the tubes at their resonant frequency when interacting with the fluid. Due to the Coriolis force, a phase shift in the tube oscillations can occur. Specifically, when no flow rate is present, the tube oscillates in phase, and the displacements are symmetrical. With flow present, the flow rate causes deceleration of the oscillation at the tube inlet and acceleration at the outlet, resulting in tube oscillations no longer being symmetrical to the centerline.

Table 1 summarizes the key characteristics of gas meters collected from the literature, including the main components, typical uses, sizes, and fundamental metrological properties.

Table 1: Design and metrological characteristics of gas meters installed in NG grids.

	Turbine	Rotary piston	Ultrasonic	Diaphragm	Thermal mass	Coriolis
Main components	Body, flow straightener, rotor, bearings and shaft	Body, measuring cartridge and rotor	Body, transducers, electronics, data processing and presentation unit	Enclosure and membranes	Body and temperature sensors	Body, sensor and the transmitter
Sector	Mainly trans.	Mainly trans.	Both trans. – distr.	Mainly distr.	Mainly distr.	Trans. (little use)
Size range	Up to G16000 (25.000 m^3/h)	Up to G1000 (1600 m^3/h)	Up to 120.000 m3/h or DN1400	Up to G100 (160 m^3/h)	More than 6000 Nm^3/h	Order of hundred thousand of kg/h
Applications	Fiscal & process	Fiscal & process	Fiscal & process	Fiscal	Fiscal & process	Mainly Process
Turndown	1:20 at atm. pressure Up to 1:30 / 1:50 by increasing pressure	1:160	1:150 (Inline configuration)	1:160	up to 1:100 (standard) 1:1000 (special)	> 1:500
Repeatability	0.1% or better	0.1% or better	± 0.05% – 0.1% or ± 0.15% (Inline / clamp on)	$Q_t \leq Q \leq Q_{max}$ 0,6%	$Q_{min} \leq Q \leq Q_t$ 1.0% $Q_t \leq Q \leq Q_{max}$ 0,6%	± 0.25%

Q_{max}, Q_{min} and Q_t are respectively the maximum, minimum and transitional flow rates of the meter

3.2 Gas quality analyzers

Gas quality analysis is essential to correctly assess the energy transported and delivered to the final end-users. Until the introduction of chromatographs in 1952, the analysis of combustible gases was conducted exclusively using chemical absorption and/or combustion methods. Chromatography gradually replaced these old measurement methods with the advent of chromatographs in the U.K. in the early 1960s (Wallis, 1986).

The technique allows for the analysis of the composition of a hydrocarbon mixture. Devices with the same main components and functionalities are available for both fixed installations and portable applications. The separation of gas components is achieved through a series of partitions between a moving gaseous phase and a stationary liquid phase held in a small diameter tube called a column. A detector then monitors the gas flow composition as it emerges from the column, carrying the separated components by measuring specific chemical or physical properties. The resulting signals are acquired for data analysis (Bartle, 2022).

The critical element is, therefore, the column, whose selection depends on the analyte's chemical nature and especially on the molecular interactions between the analyte and the stationary phase. The sample gas is mixed with a carrier gas to facilitate the detection of the main components. The choice of carrier gas depends on the application and the components to be identified. The different elements of the gas are separated in the column because they move at different speeds. Since it might take a long time and columns to complete the separation, multiple small columns speed up the analysis.

Chromatographic analysis has gained popularity because it is affordable and offers a detailed analysis of gas properties. However, a limitation is related to the sampling frequency, usually every 1.5–25 minutes, although some developments allow results to be obtained every 4 minutes, according to Wallis (1986). It is important to note that current technology cannot measure the H_2 content in H2NG mixtures (Dudek et al., 2024).

4. Overview of installed measuring devices in Italian natural gas transmission networks

4.1 Methodology

Data collection activity has been carried out in different steps. First, the measuring devices typically installed in the NG infrastructure were identified. For this purpose, the primary transmission operator was asked to provide data about the installed measuring devices in its networks concerning manufacturer, model, technology, size, and the number of installed devices. Upon receiving the data, a quality check was performed to identify any missing or erroneous information. The data were then analyzed and categorized. Finally, technical datasheets and manuals were also examined to evaluate the measuring devices' typical characteristics. A comprehensive overview was gained, with anonymised and normalised data for confidentiality and security reasons.

4.2 Gas meters

The Italian transmission gas network extends 37,000 km and has approximately 30 fiscal meters installed per 100 kilometres. One of the first pieces of data that emerged from the analysis is that there are 33 manufacturers of such devices, but only four cover more than 60% of the total market.

The technologies used are mainly turbine, rotary, and ultrasonic gas meters. Coriolis and diaphragm meters account for only a few dozen units, while no thermal mass meters are used for fiscal purposes. In percentage terms, turbine meters represent 58% of the installed units, rotary piston meters 28%, and ultrasonic meters 13%. Figure 1 shows the distribution of the technologies as a function of size. The most significant number of meters have a size between G100 (Q_{max} = 160 m³/h) and G1600 (Q_{max} = 2500 m³/h). The leading technologies are distributed over different ranges. Turbine meters are installed in pipelines over the size of G100, whereas the distribution of rotary meters is higher below the size of G400 with a peak at G100. Ultrasonic meters have a lower distribution rate but are distributed similarly to turbine meters.

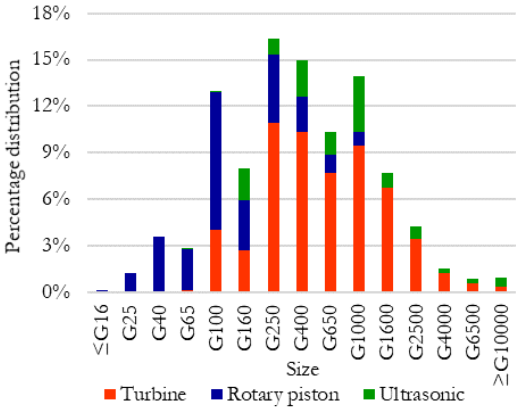

Figure 1: Distribution of meter technologies to size.

Other information obtained concerns usage, as depicted in Figure 2. Civil users represent the largest group with the highest concentration in the G250 – G1000 range. Industrial users are also widely distributed but have a more significant presence between sizes G100 and G1600. Auto-traction users require smaller sizes and have a peak at G40. Lastly, thermoelectric users have much lower rates than others and, although distributed across the entire range, see a greater concentration between G2500 – G6500.

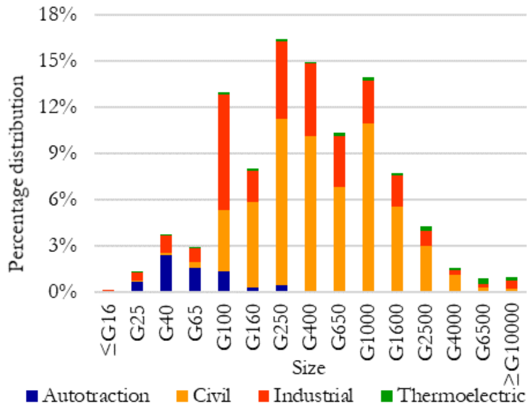

Figure 2: Distribution of meter uses to size.

Concerning the pressure at which these meters are used, the maximum operating level is 75 bar. However, most meters operate between 1 and 5 bar. Regarding the technologies, Coriolis meters are predominantly used for high pressures; diaphragm meters do not support pressures higher than 5 bar. In contrast, rotary, turbine, and ultrasonic meters are used across the entire pressure range.

4.3 Gas chromatographs

In the Italian transmission infrastructure, nearly 400 gas chromatographs are installed, 48% of which are in AOP. The market comprises eight manufacturers, with only 2 covering 75% and 28%, respectively. As shown in Figure 3, regarding their uses, these instruments are primarily employed in the AOP, followed by industrial, civil, thermoelectric, and mobility users.

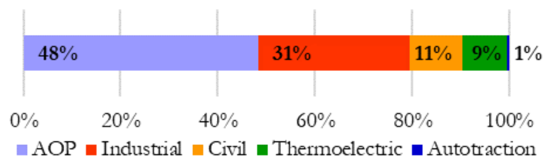

Figure 3: Distribution of gas chromatograph uses.

5. Evaluation of effort for network repurposing

The activity of collecting data on the distribution of measuring instruments in European networks developed into the THOTH2 project (Task 1.1) represents a fundamental preliminary step toward understanding how to repurpose the gas network for hydrogen. As mentioned for gas chromatographs, the devices might not support hydrogen mixtures in some cases. Therefore, to evaluate the effort of replacement, it is also essential to know the hydrogen threshold allowed.

In the literature, Marcogaz (2023) proposes a method that concludes that repurposing the existing gas grid is much more feasible than creating a new hydrogen infrastructure from an economic point of view. A similar and more straightforward but systematic approach can be carried out. Thanks to the support of the results of Task 1.2 (Dudek et al., 2024), it can be evaluated how many meters will have to be replaced in some different hydrogen concentration scenarios: 5%, 10%, 20%, 30%, and 100%.

According to the results, all meters are considered adequate for a hydrogen concentration in natural gas of 10% vol. The literature confirms this, as the questionnaires addressed to manufacturers and the technical data sheets examined. Focusing on rotary piston meters, some tests have shown that, up to 20% hydrogen, the indication errors fall within the maximum permissible error limits. However, there could be a shift towards harmful mistakes.

The information received from manufacturers is generally more optimistic. Some turbine meter producers confirm the possibility of using the devices up to a maximum concentration between 25% and 100%. For rotary piston meters, all manufacturers who provided their data state the use of the instruments up to 30%, and many up to 100%. For ultrasonic meters, the confirmation is up to 30%. For diaphragm meters, one manufacturer confirms the possibility of use up to 100% (even though tests reached 30%), while another affirms the adequacy of tests at a concentration of 100%. Regarding Coriolis meters, the experience of THOTH2 partners and manufacturers confirms the possibility of use up to 100%. Producers say they are suitable for thermal mass meters, and one has been tested up to 30% by volume.

However, to allow use for fiscal purposes, the meters must receive the EU Type Examination Certificate. Five turbine models have certification but only up to 10%vol. One thermal mass model is certified up to pure H2 among all the detected models.

6. Conclusions

Pipeline transportation appears to be the most relevant way to supply hydrogen. Still, some technical and safety issues need to be further addressed to ensure the injection of H_2 into existing NG grids. The paper focuses on the Italian context, where the leading transmission operator manages approximately 37,000 km of pipelines. One of the leading activities involves measurement operations to determine the energy transported through the network. For this purpose, the primary instruments used concern quantity and quality measurements, mainly consisting of gas meters and gas chromatographs. The characteristics and operating principles of these technologies and the sites where they are typically located were presented. The results collected within the WP1 framework were provided. The data include the recognition of market penetration for each model/manufacturer, the distribution of gas meter technologies based on meter size, and the number of devices installed per km of the grid.

Finally, some considerations were indicated regarding estimating the effort to reconvert the network with hydrogen based on the mixture concentrations allowed for each type of instrument. A method taken from the literature calculates that, from an economic point of view, converting the existing gas network is much more feasible than creating a dedicated hydrogen infrastructure.

Acknowledgements

The THOTH2 project has received funding from the Clean Hydrogen Partnership under Grant Agreement No 101101540. This Partnership gets support from the European Union's Horizon Europe Research and Innovation program, Hydrogen Europe and Hydrogen Europe Research.

Progetto finanziato dall'Unione Europea – Next Generation EU – Piano Nazionale di Ripresa e Resilienza (PNRR) – Missione 4 Componente 2 Investimento 1.3 – Avviso N. 341 del 15.03.2022 del Ministero dell'Università e della Ricerca (MUR).

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