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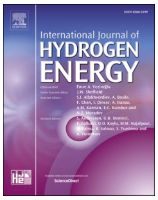

# Hydrogen in natural gas grids: prospects and recommendations about gas flow meters

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ABSTRACT

To inject green hydrogen ($H_2$) into the existing natural gas (NG) infrastructure is one way to decarbonize the European energy system. However, asset readiness is necessary to be successful. Preliminary analysis and experimental results about the compatibility of hydrogen and natural gas mixtures (H2NG) with the actual gas grids make the scientific community confident about the feasibility. Nevertheless, specific technical questions need more research. A significant topic of debate is the impact of H2NG mixtures on the performance of state-of-the-art fiscal measuring devices, which are essential for accurate billing. Identifying and addressing any potential degradation in their metrological performance due to H2NG is critical for decision-making. However, the literature lacks data about the gas meters' technologies currently installed in the NG grids, such as a comprehensive overview of their readiness at different concentrations while data are fragmented among different sources. This paper addresses these gaps by analyzing the main characteristics and categorizing more than 20,000 gas meters installed in THOTH2 project partners' grids and by summarizing the performance of traditional technologies with H2NG mixtures and pure H2 based on literature review, operators experience and manufacturers knowledge. Based on these insights, recommendations are given to stakeholders on overcoming the identified barriers to facilitate a smooth transition.

| List of acronyms | |
|---|---|
| AISI | American Iron and Steel Institute |
| ASME | American Society of Mechanical Engineers |
| ATEX | ATmosphères EXplosibles |
| CCA | Constant current anemometer |
| CTA | Constant temperature anemometer |
| DN | Nominal diameter |
| DSO | Distribution System Operator |
| EN | European Standards |
| H2NG | Hydrogen enriched natural gas mixture |
| ISO | International Organization for Standardization |
| MID | Measuring Instruments Directive |
| MPE | Maximum Permissible Errors |
| NBR | Nitrile Butadiene Rubber |
| NG | Natural gas |
| PN | Nominal pressure |
| RES | Renewable Energy Sources |

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|---|---|
| SoA | State of the Art |
| TSO | Transmission System Operator |
| **List of symbols** | |
| CO | Carbon monoxide |
| $CO_2$ | Carbon dioxide |
| $H_2$ | Hydrogen |
| Ni | Nickel |
| nfgk | Number of fiscal gas meters per km of network |
| npgk | Number of process gas meters per km of network |
| $N_{fgd}$ | Number of fiscal gas meters' models per technology |
| Nfgm | Number of fiscal gas meters' manufacturers per technology |
| $Q_{max}$ | Maximum flow rate |
| $Q_{min}$ | Minimum flow rate |
| $Q_r$ | Overload flow rate |
| $Q_t$ | Transitional flow rate |
| $r_{pfg}$ | Ratio between process and fiscal gas meters |
| $\chi_{fgt}$ | Fiscal gas meters' technology penetration |
| $\chi_{fgs}$ | Fiscal gas meters' technology per size penetration |

## 1. Introduction

The exploitation of hydrogen ($H_2$) is a promising solution for addressing climate change and decarbonising the energy sector. Being considered a versatile energy carrier, $H_2$ can be used across multiple domains of energy usage, including hard-to-decarbonize industries (e.g., chemical, petrochemical [1] and steelmaking [2]) and the transportation sector [3]. Fig. 1 summarises the broad spectrum of $H_2$ production processes and applications. However, the processes applied to generate $H_2$ could have a substantial carbon footprint. $H_2$ can be produced through direct solar water decomposition or via thermochemical, electrolytic, and biological processes [4,5], utilising both renewable energy sources (RES) and non-RES. Currently, steam reforming of natural gas (NG) is recognized as the most feasible technique for $H_2$ production. However, due to the escalating costs of NG and concerns over carbon dioxide ($CO_2$) emissions, there is an increasing need for the development of environmentally friendly and sustainable production solutions. Currently, the commercial use of biomass gasification for $H_2$ production is still challenging [6] and attention is given to the production from other RES, e.g., photovoltaic and wind plants.

Blending or transport renewable $H_2$ in the NG networks has an interesting potential for decarbonising the energy system and reducing greenhouse gas emissions. Furthermore, $H_2$ injection into NG grids could also contribute to energy balancing purposes by storing the excess energy, thus matching renewable energy generation and consumption [7]. Therefore, the existing large-storage facilities, originally constructed for fossil fuel distribution, could be combined with distributed $H_2$ production through direct injection into pipelines, also supporting long-term storage [8,9] or in underground storage. For this case Zivar et al. [10] reviewed underground $H_2$ storage including different modes like depleted hydrocarbon reservoirs, aquifers, and manmade underground cavities. The result of the research shows that experience is still scarce and that geological conditions are essential to define the site location since they affect the operational costs, efficiency and potential risks during the entire lifetime.

Regarding $H_2$ blending or pure $H_2$ transport there are two scenarios. In the first scenario, $H_2$ is injected into the NG network, transported over a specified distance, and then isolated from the NG stream through separation technologies. Once separated, $H_2$ is utilized in various technologies and processes, including as a fuel in fuel cells or as a reactant in chemical processes [11]. In the second scenario, it serves as a renewable component in the NG, in conventional or specific applications [12].

$H_2$ blending in actual NG networks presents several operational, safety, and economic aspects that require evaluation and strategies, as shown in Table 1 and further discussed below. First, $H_2$ blending requires the management of pressure fluctuations and strict gas quality controls to remain within technical limits. Infrastructure must be flexible and adaptable, capable of managing new operational demands and fluctuations.

From the safety point of view, $H_2$ leakages as well as altered combustion properties, requiring enhanced fire management strategies and

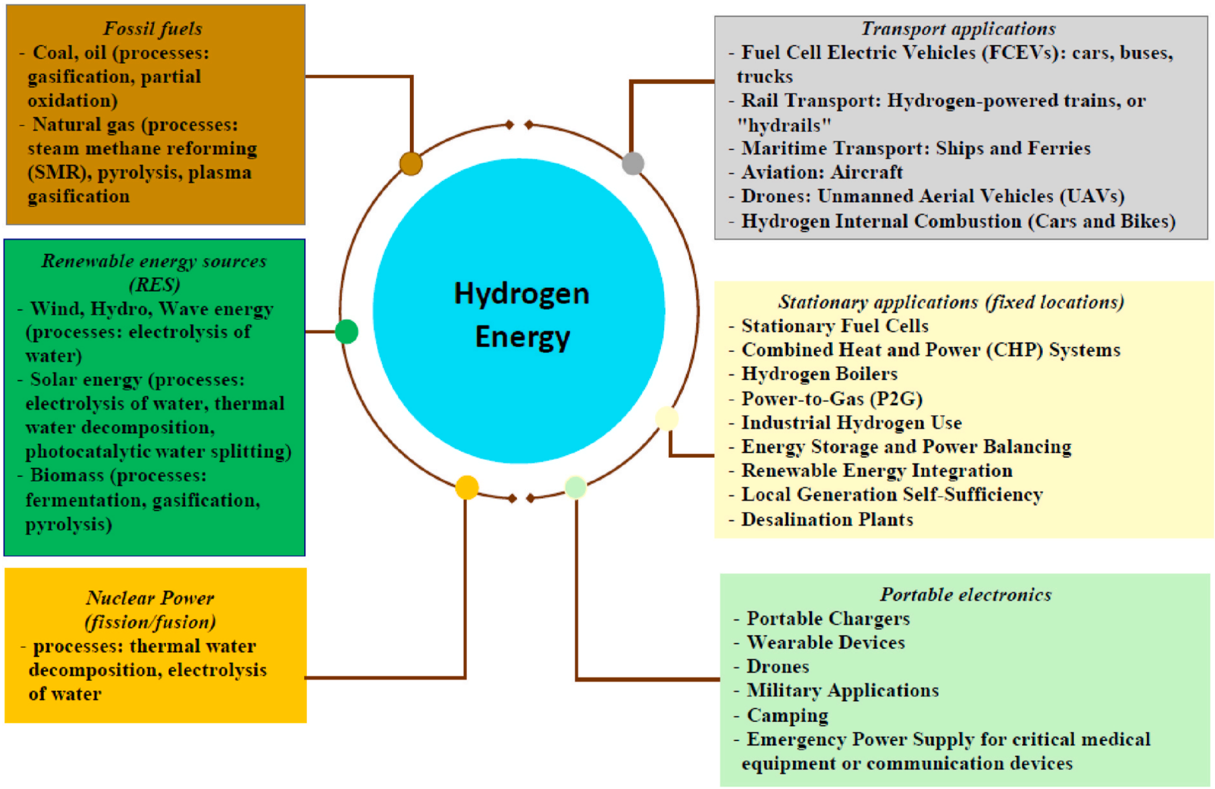


**Fig. 1.** Production and use of hydrogen as a clean and versatile energy carrier.

**Table 1**

Aspects related to blended hydrogen in NG networks (adapted from Ref. [12]).

| Operational | Safety | Economic |
|---|---|---|
| - *metering accuracy* (the presence of small hydrogen particles can increase leakage and reduce measurement accuracy; the relatively high speed of sound and low density can lead to inaccuracies in measurement)<br>- *operation and system impacts* (operational efficiency, system compatibility, operational procedures, control and monitoring, energy transmission, system adaptability, end-user applications, regulatory compliance, environmental impact, etc.)<br>- *pressure variation through pipelines* (when blending hydrogen with NG, managing pressure is critical due to the distinct properties of hydrogen. Hydrogen has a lower density and higher diffusivity compared to NG, which can lead to different flow dynamics and pressure behaviours within the pipeline system)<br>- *assessment of gas composition* (hydrogen concentration, calorific value, Wobbe index, density and viscosity, pressure and temperature, moisture content, impurities, combustion properties)<br>- *technical limits of facilities* (material compatibility, blending ratios, equipment specifications, metering and measurement, storage capacity, combustion characteristics)<br>- *infrastructural flexibility* (the capability of the existing infrastructure to adapt, accommodate, and efficiently operate with the introduction of hydrogen, without compromising safety, reliability, or performance) | - *metal embrittlement for pipelines, compressors, storage, etc* (hydrogen can cause metal embrittlement, where the metal becomes brittle and more prone to cracking and failure, including leaks and ruptures)<br>- *leakages in pipe joints, seals* etc (leakages can lead to the accumulation of hydrogen, creating explosive atmospheres and increasing the risk of fires and explosions)<br>- *low Wobbe Index impacting combustion efficiency* (a low value may lead to incomplete combustion, producing carbon monoxide CO, which is a hazardous gas)<br>- *differences in combustion properties* (the altered combustion properties necessitate modifications to combustion systems, and stringent control measures ensure safe combustion and handling)<br>- *fire management* (proper fire detection, suppression, and management systems are crucial for hydrogen-handling facilities)<br>- *environmental impacts* (leakages lead to atmospheric pollution and have an indirect environmental impact; the various hydrogen production technologies have significant environmental footprints if derived from non-RES technology)<br>- *compatible electrical equipment* (the adaptability of electrical equipment and devices within the gas infrastructure to function safely and efficiently with the hydrogen presence) | - *infrastructural modifications and improvements (*to handle hydrogen due to its unique properties compared to NG)<br>- *switching costs* (end users can pay additional costs to adapt their appliances and systems to use blending hydrogen with NG efficiently and safely; strategies to minimize or subsidise switching costs may be needed to encourage the adoption of blending hydrogen with NG)<br>- *variable* hydrogen *production costs* (variability in production costs can affect the price stability of blending hydrogen with NG)<br>- hydrogen *separation* (in the supply chain, it might be necessary to separate hydrogen from the NG, which can be a complex and energy-consuming process) |

environmental safeguarding, have to be evaluated [13,14]. Focusing on material compatibility, $H_2$ injection into natural gas poses different technological issues on material compatibility [15,16]. Among these, the effect of $H_2$ on metallic components of the measuring devices imposes heavy limits on meter's life, possible inaccuracies in measurement, and safety concerns. $H_2$ is known to reduce toughness and increase fatigue crack growth rates, especially at high pressure and high temperature [17–19]. When considering the use of existing NG networks for $H_2$ transportation, it is essential to verify whether the metallic materials are compatible with $H_2$ gas service and in particular whether the chemical composition of the steel meets the relevant requirements (ASME B31.12 [17]) since the penetration of $H_2$ molecules can degrade the mechanical properties of metals, impacting plasticity, ductility, and fracture toughness [18]. Therefore, $H_2$ injection requires verifying the compatibility of the components currently installed in the grids [22–28]. San Marchi et al. [19] reviewed the reference documents to be considered when selecting materials in contact with gaseous high-pressure $H_2$. Sofian et al. in a very recent paper offer a comprehensive analysis of current research and technological applications in $H_2$ blending within gas networks focusing on corrosion and $H_2$ embrittlement [20]. The effects of the $H_2$ environment on the embrittlement of steel pipelines, valves and welds, and measurements, such as coatings, were studied and adopted to mitigate them. The effect of $H_2$ on valves and welds was published by Jia et al. [21]. Nitrile Butadiene Rubber (NBR) behaviour in the presence of $H_2$ was experimentally investigated by Simmons et al. finding a potential reduction in the sealing performance due to the increase in the compression set after $H_2$ exposure [22]. Among the degradation effects induced by the physicochemical interactions of $H_2$ with metal components, corrosion was studied mainly on pipelines and valves rather than on meters as the carbon steels of pipelines (such API 5 L X42, X52, X60, X65, X70, X80) are expected to be more attacked than the metallic meter's materials, essentially stainless steel and aluminum. Wet $H_2S$, $CO_2$, and other impurities present in the H2NG cause electrochemical corrosion of the pipeline steel and generate corrosion products such as FeS and $FeCO_3$, resulting in corrosion failure of pipelines. Moreover, $H_2$ atoms entering the interior of the steel polymerize to form $H_2$ molecules in the internal defects, which deteriorate the mechanical properties and cause $H_2$ embrittlement failure of the pipeline. Corrosion and $H_2$ embrittlement of pipeline steel have coupling and competing effects [20]. Among the alternative fuels that could substitute NG in the existing gas grids, potential corrosion effects on meters are envisaged by the NewGasMet results of Deliverables D1, D3, and D5, with biogas containing $H_2S$ streams rather than with H2NG blending [23–25]. Deliverable D3 reported that gas meters with mobile parts, e.g., turbine, rotary and diaphragm gas meters were tested with raw biogas and that they were destroyed after about one day. No specific problems were instead identified for ultrasonic gas meters. Unfortunately, the results were confidential and no more details were provided. Material mechanical degradation, caused by corrosion as well as other physiochemical processes, can be evidenced by studying the effect of $H_2$ and/or H2NG on meter's performances after long periods of exposure. Leakage and meter accuracy were investigated in the NaturalHy Project-Work Package 3 and 4. The deviation of different gas meter readings with H2NG mixtures was found acceptable when measuring a gas mixture containing less than 50% $H_2$ [16]. Domestic gas meters material compatibility with H2NG, including the degradation due to corrosion was experimentally studied by Jaworski et al. [26,27] performing experiments aimed at assessing the effect of $H_2$ in terms of durability of domestic gas meters. They tested 105 gas meters (diaphragm and thermal mass) of different sizes and manufacturers, both brand-new and withdrawn from service in terms of accuracy drift after durability cycles of 5000 h and 10,000 h with H2NG mixtures and $H_2$ concentration of 10%vol. and 15%vol. For the tested samples no significant metrological influence was found on the obtained average drift of errors after the durability tests. Sanchez-Lainez et al. performed a durability experiment on a platform replicating a high-pressure gas grid, using a turbine flow meter [28]. No embrittlement or other kind of damage were found on the flowmeter after 3000 h exposure to 20%vol, 80 bar H2NG. The NewGasMet project also verified the effect of exposure to $H_2$ and biogas for a year on diaphragm and thermal mass domestic gas meters while the ultrasonic type was tested only with biogas [23]. Diaphragm gas meters showed no or limited modifications on the diaphragm of one of two models while consistent deposits were found in case of biogas due to nucleation of biogas contaminants ($H_2S$) but also due the condensation ad subsequent evaporation of moisture. As for diaphragm, thermal gas meters showed no effect due to $H_2$, while corrosion and chemical modification of the surface of the electrical contacts were observed when tested with raw biogas. Downstream the meter, the non-combustion related aspects of injecting $H_2$ into the gas distribution networks within buildings, including $H_2$ embrittlement of metallic materials, chemical compatibility and leakage issues were studied by the THYGA project. The results showed that low alloy steels are the most susceptible materials to $H_2$ embrittlement, followed by stainless steels, aluminum, copper and brass alloys [29]. At the relative pressures of the operating conditions of gas distribution network in buildings, between 30 and 50 mbar, a gas mixture composed of NG and up to 50% $H_2$ should not be problematic in terms of $H_2$ embrittlement for any of the metallic materials used in gas distribution networks, unless high mechanical stresses are applied. The chemical compatibility of $H_2$ with other materials, specifically polyethylene (PE), was also discussed. PE was found to have no corrosion issues, and no deterioration or ageing was observed after long-term testing in $H_2$ gas.

Another aspect to be ensured is proper injection. A dedicated plant has to be designed to ensure the homogeneity of the mixture downstream by Khabbazi et al. [30]. The variations in supply and demand, combined with the inherent inertia, considerable delay found in NG networks, and the characteristics of $H_2$ concentration distribution parameters, raise the uncertainty of the dynamic characteristics of NG networks. The $H_2$ low density can lead to various gas dynamics during leak incidents, which may render traditional leak detection systems incompatible with pipelines carrying a hydrogen-enriched NG (H2NG) mixture [31]. Many other studies are available allowing to understand and support the safe transition to $H_2$. For example, Liu et al. addressed $H_2$ stratification in the pipeline due to the different densities of the gases in the mixture [32]. Wang et al. [33] proposed a model to calculate the leakage from a buried pipeline and the hazard of the leak compared to NG allowing to calculate the risk in the case of failure. Tian & Pei [34] proposed a review aiming to integrate knowledge about material compatibility and safety aspects when transporting H2NG mixtures [29]. From an economic point of view, H2NG or pure $H_2$ transport involve additional costs related to infrastructure upgrades and adaptations required by end-users, coupled with the variable costs of $H_2$ production and separation processes [35,36].

On the user side, different applications of $H_2$ and H2NG mixtures are under investigation. A distinction between high-pressure and low-pressure final uses when assessing practical implementations. In low-pressure systems, $H_2$ can be supplied from the gas distribution grids as an alternative to NG for heating spaces, production of hot water, and cooking. $H_2$ has different combustion properties than NG, requiring specialized burners and safety systems to handle its wider flammability range and lower ignition energy [37–39]. Several factors influence whether appliances can work with different gases, such as the Wobbe index (which helps determine if a gas is suitable for an appliance), combustion velocity, and burner design. The natural gas composition varies across Europe, leading to different Wobbe index standards in different countries. If an incompatible gas is used, this can lead to problems like incomplete combustion, the flame going out, or the burner overheating. Pure $H_2$ has a Wobbe index of about 48 $MJ/m^3$ [40–42], and this value is within the safety range for burners in some European countries [41]. The Wobbe Index, related to heat input, is critical for ensuring that appliances deliver the required thermal output for heating and cooking. The laminar burning velocity affects flame stability, posing risks such as flashback, where the flame moves back into the burner, potentially causing damage or dangerous gas leaks, also impacting higher needs and costs for maintenance. Laboratory studies have shown that $H_2$ increases the burning velocity, but practical tests on a limited number of home appliances have not observed flashback [43–45]. Home appliances designed for NG cannot generally use $H_2$ directly because it has a much higher flame speed. This makes flame control more difficult and requires different burner designs. Therefore, existing burners would need to be retrofitted or replaced to use $H_2$ instead of NG. This replacement process can be complex and costly, as it involves not only the physical replacement of the burners but also the recalibration of the entire heating system to ensure optimal performance with the new gas [41]. $H_2$ also encounters safety aspects. $H_2$ is highly flammable, necessitating careful handling and storage to ensure safety. Home appliances that use $H_2$ need to be designed and tested to meet strict safety standards to prevent accidents such as leaks and explosions. The infrastructure for $H_2$ is less developed compared to NG, and significant investment is needed to build a safe and reliable $H_2$ supply network [38]. Home appliances, numbering in the hundreds of millions in regions like the EU, vary widely in type, design, and age. This diversity complicates the prediction of appliance performance with $H_2$ admixture, as these appliances were originally designed for NG, which has consistent combustion properties [43,46,47]. Home appliances such as boilers, stoves, and heaters that currently use NG will need modifications to operate safely and efficiently on $H_2$. When used as a fuel, $H_2$ produces only water vapour, significantly reducing greenhouse gas emissions compared to fossil fuels. Recent research on the application of $H_2$ mixtures in both internal combustion engines and atmospheric burners has shown that the carbon monoxide (CO) and $CO_2$ levels resulting from burning H2NG blends are lower than those produced by any other gaseous fuels [48]. However, the method of $H_2$ production can have environmental impacts, especially if it involves fossil fuels without carbon capture. Therefore, the environmental benefits of $H_2$-powered appliances are closely linked to the sustainability of the $H_2$ production process [38]. Initially, $H_2$-powered appliances are likely to be more expensive than their NG counterparts due to the costs associated with developing and scaling up new technologies. However, as $H_2$ production becomes more efficient and widespread, the costs are expected to decrease. This could lead to lower long-term fuel costs and more stable energy expenses for consumers [38,49]. Several companies are actively developing $H_2$-compatible appliances, including boilers and fuel cells (e.g., Bosch [50], Vaillant [51], Ariston [52], Viessmann [53], Honeywell [54], BDR Thermea [55], etc). In addition to the companies mentioned before, many other companies are investing in the research and development of $H_2$-compatible appliances. These appliances aim to provide a familiar user experience while leveraging the clean energy potential of $H_2$. On a different prospect, $H_2$ addition to NG holds promise for reducing $CO_2$ emissions. However, its impact on the large and varied population of home appliances must be carefully managed. The technical issues referring to the use of NG enriched with $H_2$ to supply the final uses need to be assessed to understand whether different gas mixtures can be safely and effectively used in existing appliances without significant performance deterioration [56]. In particular, the impact of supplying premixed combustion appliances such as home condensing boilers with different gas mixtures has to be further investigated [9]. The interchangeability analysis extensively presented by De Vries offers a practical approach to bridging the knowledge gap, ensuring that $H_2$ admixtures can be safely integrated into existing gas infrastructures without extensive and costly appliance testing [43]. The interchangeability analysis is also particularly useful for identifying acceptable $H_2$ fractions in NG, ensuring that modifications to the gas supply do not compromise appliance performance or safety. The crucial role of people's perception in the transition to home appliances with the integration of $H_2$ has been discussed in Refs. [57,58]. Consumer appliances marketed in Europe since the 1990s are regulated by the Gas Appliances Directive, which was updated to the Gas Appliances Regulation in 2019, i.e., the Regulation (EU) 2016/426 [59]. These appliances, as per the established testing protocols, must be capable of handling an $H_2$ molar fraction of up to 23% [60,61]. Public knowledge about $H_2$ is limited, particularly regarding its physical and chemical properties, compared to other low-carbon technologies for heating and cooking, while public acceptance is strongly dependent on safety concerns [62]. However, $H_2$ blending with natural gas could be seen as a more viable solution [63]. In summary, for $H_2$ appliances to be successfully integrated into homes, it is crucial to address safety, cost, and maintenance concerns and enhance public knowledge and acceptance through targeted information and engagement strategies.

The use of the transmission gas network to convey H2NG mixtures or pure $H_2$ to high-pressure end-users can be an option when large renewable gas flowrates have to be supplied over along long distances [64,65]. Among these, industrial hard to abate [66,67], energy generation [68] or refuelling stations [69] could benefit from the operation of $H_2$ grids. Furthermore, high-quality $H_2$ streams can also be obtained from the H2NG mixtures by separation of the molecules of the different gases through several technologies, as recently reviewed by Allden [76]. Otherwise, the onboard production concept is an alternative. The concept simply relies on the production of $H_2$ near the users, simplifying the supply chain from the production to the final end-users. Examples in the literature refer to applications like ships, gas turbines, and locomotives where onboard production would avoid modification to the existing NG infrastructure [70–72]. For example, Pashchenko [71] investigated the two alternatives for the supply of a gas turbine aiming to evaluate the effect on the reduction of carbon footprint. As expected, the "blending case" would not affect the users' plant configuration while the "onboard case" would require additional components, including a reformer supplied by a local renewable source, i.e., solar heat. Waste heat was instead considered in the cases developed by Dere et al. [72] and Al-Hamed & Dincer [70]. A similar approach, consisting of powering refuelling stations with onsite wind turbines, was studied by Chrysochoidis-Antsos et al. [73]. In the developed case, however, the plant was also connected to the NG grid in order to accommodate injection or supply to/from the grid in the case of mismatch between production and demand. Furthermore, since the difficulties in transporting heat over long distances [74], other factors like local renewable or waste energy availability, land requirements dedicated to the renewable plants, and communities' opposition [75,76] have to be considered for onboard production.

The reconversion of the existing NG infrastructure to convey $H_2$ as pure stream or blended would allow exploiting locations with a huge renewable potential already connected to the grids [77–79]. Despite the abundance of literature on $H_2$ blending in the existing NG infrastructure, some research questions still need answers. Among the components installed in the NG transmission and distribution grids, gas meters are used for billing purposes and to monitor the flow along the networks [80]. The Measuring Equipment Directive (MID) is the normative reference [81].

Researchers have only recently started evaluating the effect of $H_2$ on the devices currently operating in the grids. Recent studies have shown that adding hydrogen to natural gas impacts the physicochemical properties of the gas mixture, affecting the metrological properties of household gas meters, including thermal gas meters. These studies emphasize the need for precise measurements under varying conditions of ambient and gas temperatures to ensure long-term measurement accuracy and operational safety in the gas distribution network [80,82]. Additionally, research has also highlighted that the injection of hydrogen impacts thermodynamic properties such as density, calorific value, and Wobbe index, which in turn affects the accuracy of volume and gas quality measurements [83] The study presented in this paper aims to provide a comprehensive understanding of the state-of-the-art on how H2NG mixtures impact different gas meter technologies (turbine gas meters, rotary piston gas meters, ultrasonic gas meters, diaphragm gas meters, thermal mass gas meters, Coriolis gas meters, and calibrated orifice plates). By reviewing aspects concerning metrological performance, material compatibility, long-term durability, safety, regulatory requirements, and economic implications in our paper, the aim is to provide information to interested stakeholders (e.g., gas meters' manufacturers and gas DSOs and TSOs) allowing the reliable integration of $H_2$ into NG grids. This research is essential for ensuring that gas flow meters can continue to provide accurate and reliable measurements in applications where $H_2$ plays a significant role in the energy mix.

The present study specifically addresses two critical research questions that have been missing in the existing literature. Firstly, it aims to recognize the gas meters' technologies and sizes in European NG transmission and distribution grids to evaluate the effect of $H_2$ on NG grids' metrological aspects. Secondly, it provides a summary of the existing technological knowledge about gas meters' technological readiness, as that provided by Gislon et al. for the normative framework [84], is needed.

To cover this gap, this paper provides an overview and appraisal of the impact of H2NG mixtures on state-of-the-art gas meters indicated in ISO 1776 [85] and typically installed in NG distribution and transmission grids from the perspective of the THOTH2 project ("*Novel meTHOds of Testing for measurement of natural gas and Hydrogen mixtures*"). The suitability of the identified measuring devices in existing grids for $H_2$ blending is provided based on a literature review, the project partners' know-how, and the feedback received from manufactures through a dedicated survey. Following this analysis, a discussion and recommendations for further research activities are provided. The paper is structured as follows: Section 2 describes the methodology and the indicators selected for the assessment of gas meters SoA in European NG transmission and distribution grids are described. Section 3 presents a review of the main gas meters' technologies focusing on the potential impact deriving from $H_2$ injection. Section 4 discusses the main results. The last section contains the conclusions.

## 2. Methodologies and indicators

The following sections outline the methodology developed for analysing the state-of-the-art gas meters installed in European NG transmission and distribution grids. They also aim to identify gaps and unanswered questions in research that are critical to support $H_2$ blending or pure $H_2$ transport.

### 2.1. Data collection

Data collection was performed by means of surveys, questionnaires, and interviews with recognized experts of the sector. Experts' surveys are very useful for analysing concepts that are otherwise very difficult or impossible to explore through traditional methods [74,86,87]. In this analysis, the experts were identified among European NG Transmission and Distribution System Operators (TSOs and DSOs), relevant sector associations (i.e., Marcogaz, and Farecogaz), and manufacturers of those devices that are currently installed in NG grids. For confidentiality reasons, all the answers have been anonymized.

#### 2.1.1. Data collection from gas TSOs and DSOs' experts

The questions were prepared to collect the main characteristics of the installed gas meters. For NG transmission grids, four project partners were involved in the data collection. The following data were collected.

1. The total length of the operated NG grid
2. The total number of measuring devices installed in the NG grids.

For all the installed devices, the following data were also collected.

3. The gas meters' technologies.
4. The size and diameter of the installed meters (if applicable).
5. The gas meters' manufacturers and models.

To enlarge the vision, a survey was also circulated among NG TSOs and DSOs outside the Consortium.

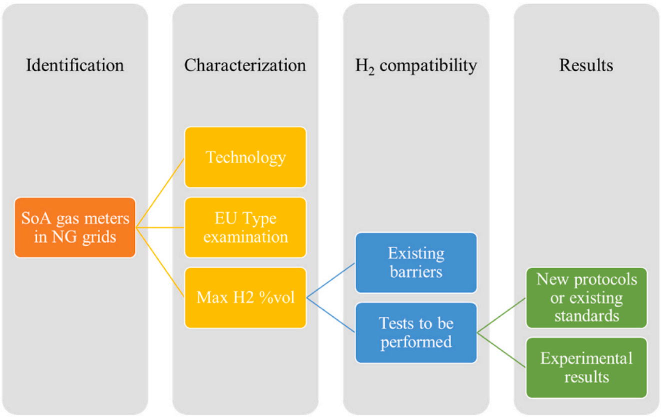


**Fig. 2.** Data collected from manufacturers surveys.

### 2.1.2. *Data collection from gas measuring devices' manufacturers*

Once the gas meters' models in European NG grids were identified, a questionnaire was sent to gas meters' manufacturers. It was decided to minimize as much as possible the open form questions [74]. Furthermore, a minimum number of open-ended questions was proposed to prevent those participants from leaving the survey before its completion. If no answer was received, $H_2$ compatibility was investigated by analysing public datasheets.

The questions facilitated the collection of the data indicated in Fig. 2.

### 2.2. *Data analysis*

Once the quality of the received data was checked, the data analysis process started. A list of indicators was designed to summarize the most significant information received (see Table 2). The selection of the indicators was driven by the need to identify the most relevant technologies, models and configurations currently installed in NG grids to be used for performing tests with H2NG mixtures or pure $H_2$.

Regarding the analysis of the responses received from the manufacturers, the partners examined the feedback. If it contradicted the information available in the state of the art (SoA), the manufacturers were directly contacted to seek confirmation and additional details.

## 3. Results and discussion

Transmission and Distribution System Operators (TSOs and DSOs) operate gas meters for fiscal and process purposes. Fiscal gas meters have to be compliant with the Measuring Instruments Directive 2014/32/EU (MID) to be commercialized and operated in the European market (Table 3).

The main results obtained from the research activity are presented in the following sections. Firstly, an overview of the gas meters installed in European NG grids is provided. Subsequently, the primary limitations of the installed technologies with respect to H2NG mixtures or pure $H_2$ are reported and discussed.

**Table 3**
Fiscal gas meters' performances compliant to MID [81].

| | Class 1.0 | Class 1.5 |
|---|---|---|
| **MPE at $Q_{min} \le Q \le Q_t$ (a)** | 2.0% | 3.0% |
| **MPE at $Q_t \le Q \le Q_{max}$ (a)** | 1.0 % | 1.5% |
| **$Q_{max}/Q_{min}$** | ≥20 | ≥150 |
| **$Q_{max}/Q_t$** | ≥5 | ≥10 |
| **$Q_r/Q_{max}$** | ≥1.2 | ≥1.2 |

**Definitions.**
MPE: Maximum Permissible Error.
$Q_{max}$: The highest flow rate at which the gas meter provides indications that satisfy the requirements regarding the MPE.
$Q_{min}$: The lowest flow rate at which the gas meter provides indications that satisfy the requirements regarding MPE.
$Q_t$: The transitional flow rate is the flow rate occurring between the maximum and minimum flow rates at which the flow rate range is divided into two zones, the 'upper zone' and the 'lower zone'. Each zone has a characteristic MPE.
$Q_r$: The overload flow rate is the highest flow rate at which the meter operates for a short period of time without deteriorating.
[a] For a gas meter with temperature conversion, which only indicates the converted volume, the MPE of the meter is increased by 0,5 % in a range of 30 °C extending symmetrically around the temperature specified by the manufacturer that lies between 15 °C and 25 °C. Outside this range, an additional increase of 0,5 % is permitted in each interval of 10 °C.

### 3.1. *Gas meters' technologies in european gas grids: an overview from THOTH2 project*

The data obtained from the relevant stakeholders allowed to design a preliminary status of the European NG transmission grids operated by THOTH2 partners [88]. By managing about 87,300 km of transmission grid, almost the 43.6% of the European gas network is covered.

The calculated performance indicators are reported in Table 4. Table 4 reports the calculated KPIs, showing that the number of fiscal gas meters typically ranges between 0.11 and 0.35 m per km of transmission grid. Process gas meters, instead, are less present in the networks due to the limited applications in which they are implemented. Gas meters' classification per technology and size is shown respectively in Fig. 3 and in Fig. 4 for the four TSOs in the THOTH2 consortium. The distribution of gas meter technologies, as depicted in Fig. 3, shows a diverse array of measurement tools in use among the THOTH2 project partners. Turbine gas meters, representing half of the technology distribution, are prominently utilized, indicating a preference for this type of technology in current infrastructures. The presence of ultrasonic gas meters at 31.5% suggests a significant adoption of this newer technology, likely due to its non-intrusive measurement capabilities and accuracy over a wide range of flow rates. Diaphragm and rotary gas meters, while less common, still play a critical role in specific applications, as evidenced by their respective shares of 13.4% and 4.9%. The category of

**Table 2**
Selected indicators.

| Symbol | Unit of Measure | Selected performance indicator | Definition |
|---|---|---|---|
| $n_{fgk}$ | [#/km] | Number of fiscal gas meters per km of network | It is the ratio between the number of fiscal gas meters installed and the total length of the network. |
| $n_{pgk}$ | [#/km] | Number of process gas meters per km of network | It is the ratio between the number of process gas meters installed and the total length of the network. |
| $r_{pfg}$ | [#/#] | Ratio between process and fiscal gas meters | It is the ratio between the number of process and fiscal gas meters. |
| $\chi_{fgt}$ | [%] or [−] | Fiscal gas meters' technology penetration | It is the number of gas meters of a specific technology divided by the total number of installed meters, independent of the size. |
| $\chi_{fgs}$ | [%] or [−] | Fiscal gas meters' technology per size penetration | It is the number of gas meters of a specific technology and size divided by the total number of installed meters. |
| $N_{fgm}$ | [#] | Number of fiscal gas meters' manufacturers per technology | It is the number of fiscal gas meters' manufacturers for each technology. |
| $N_{fgd}$ | [#] | Number of fiscal gas meters' models per technology | It is the number of fiscal gas meters' models for each technology. |

**Table 4**
Calculated performance indicators 1–4, 6–7 for the analysed NG transmission grids.

| Symbol | Selected performance indicator | Value |
|---|---|---|
| $n_{fgk}$ | Number of fiscal gas meters per km of network | 0.11–0.35 [meters/km] |
| $n_{pgk}$ | Number of process gas meters per km of network | 0.003–0.028 [meters/km] |
| $r_{pfg}$ | Ratio between process and fiscal gas meters | 0.02–0.092 [fiscal/ process] |
| $\chi_{fgt}$ | Fiscal gas meters' technology penetration | Turbine: 73.2%<br>Rotary: 12.3%<br>Ultrasonic: 6.6%<br>Diaphragm: 7.9%<br>Coriolis: 0.01%<br>Thermal mass: 0%<br>Calibrated orifices: ≈0 % |
| $N_{fgm}$ | Number of fiscal gas meters' manufacturers per technology | Turbine: 9<br>Rotary: 7<br>Ultrasonic: 12<br>Diaphragm: 9<br>Coriolis: 1<br>Calibrated orifices: Not applicable |
| $N_{fgd}$ | Number of fiscal gas meters' models per technology | Turbine: 11<br>Rotary: 10<br>Ultrasonic: 14<br>Diaphragm: Not available<br>Coriolis: 2<br>Calibrated orifices: Not applicable |

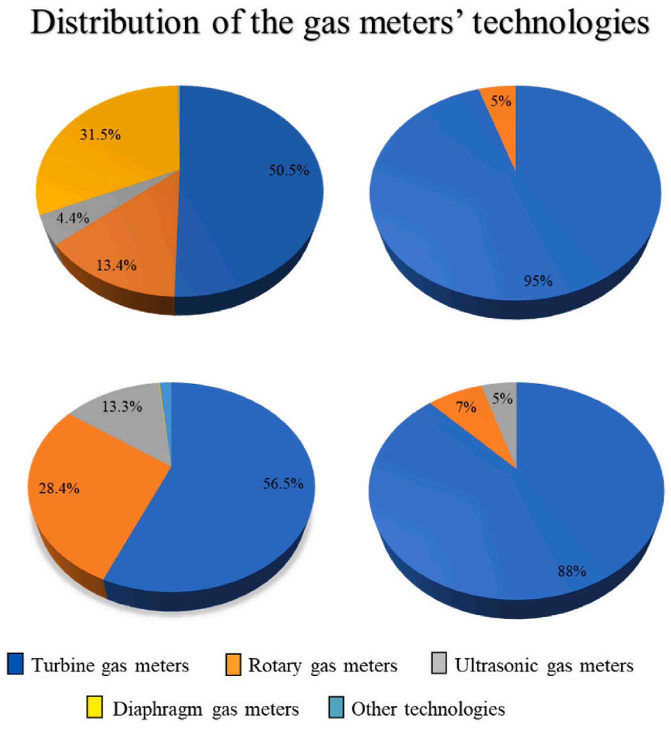


**Fig. 3.** Distribution of the gas meters' technologies among the THOTH2 partners.

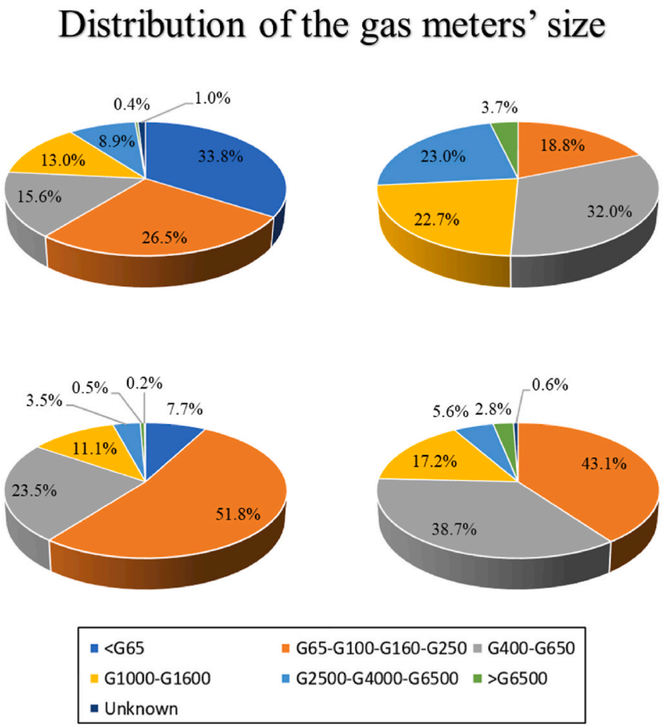
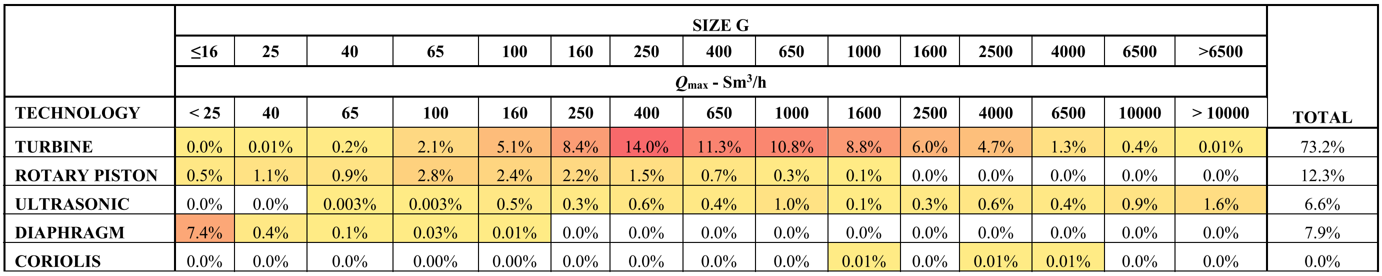


**Fig. 4.** Distribution of the gas meters' size among the THOTH2 partners.

"Other technologies" at 5% indicates the use of alternative measurement techniques, which may include newer or niche technologies that are being tested or implemented. Fig. 4 reveals the size distribution of gas meters, which is crucial for understanding the scalability and capacity of gas distribution among the THOTH2 project partners. The majority of meters fall within the G65 to G400-G650 range, with the G65-G100-G1600 category being the most prevalent at 51.8%. This suggests that the majority of the meters are designed for smaller-scale applications. The presence of larger meters, G2500-G4000-G6500, at 17.2%, and the significant minority of sizes above G6500, demonstrate the capability and readiness for handling higher volumes of gas flow, which is essential for large-scale distribution systems. The 'Unknown' category points to a data gap that could affect the understanding of distribution capabilities and indicates a potential area for further research or data verification.

Fig. 5 provides a general view as average of the reported values of the penetration $\chi_{fgs}$ for the four analysed TSOs. Regarding the technology installed, turbine gas meters are the most implemented followed by rotary and ultrasonic gas meters. The result is also confirmed by data elaborated in the Hydrogen In Gas GridS (HIGGS) project that indicates turbine gas meters as the preferred technology in European gas transmission networks [89]. As shown in Fig. 5, only one TSO indicates a high percentage of diaphragm gas meters used for billing purposes in its own small-size applications. Another one declares no use of rotary-piston gas meters. The number of Coriolis gas meters and calibrated orifices are quite limited in the investigated grids since only two partners declared their adoption in the grid. No thermal mass meter was indicated for fiscal purposes at the moment even if they are installed for process applications. The main conclusions derived from the industrial partners of the Consortium were also confirmed by the surveys received from other gas TSOs not directly involved but interested in the activities.

The performance indicators $N_{fgm}$ and $N_{fgd}$ (Table 4) show a quite fragmented result. Even if not displayed for confidentiality reasons, each TSO has prevalent models installed in their network. However, even if some models are installed in more than one TSO, the prevalent models do not match among gas TSOs. For example, nine manufacturers and eleven different models were identified for gas turbine meters. A similar conclusion applies to rotary piston gas meters. Ultrasonic gas meters are supplied by a greater number of manufacturers, resulting in a wide variety of models currently in operation within the investigated networks. Regarding Coriolis gas meters, only one manufacturer and two models have been identified. It can be explained by the slow penetration of this technology in this sector. No details can be reported about gas diaphragm meters where nine manufacturers were indicated. Unfortunately, only the commercial name of one model was available, while the



| | SIZE G | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ≤16 | 25 | 40 | 65 | 100 | 160 | 250 | 400 | 650 | 1000 | 1600 | 2500 | 4000 | 6500 | >6500 | |
| | $Q_{max}$ - Sm$^3$/h | | | | | | | | | | | | | | | |
| **TECHNOLOGY** | < 25 | 40 | 65 | 100 | 160 | 250 | 400 | 650 | 1000 | 1600 | 2500 | 4000 | 6500 | 10000 | > 10000 | **TOTAL** |
| **TURBINE** | 0.0% | 0.01% | 0.2% | 2.1% | 5.1% | 8.4% | 14.0% | 11.3% | 10.8% | 8.8% | 6.0% | 4.7% | 1.3% | 0.4% | 0.01% | 73.2% |
| **ROTARY PISTON** | 0.5% | 1.1% | 0.9% | 2.8% | 2.4% | 2.2% | 1.5% | 0.7% | 0.3% | 0.1% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 12.3% |
| **ULTRASONIC** | 0.0% | 0.0% | 0.003% | 0.003% | 0.5% | 0.3% | 0.6% | 0.4% | 1.0% | 0.1% | 0.3% | 0.6% | 0.4% | 0.9% | 1.6% | 6.6% |
| **DIAPHRAGM** | 7.4% | 0.4% | 0.1% | 0.03% | 0.01% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 7.9% |
| **CORIOLIS** | 0.0% | 0.0% | 0.0% | 0.00% | 0.00% | 0.0% | 0.0% | 0.0% | 0.0% | 0.01% | 0.0% | 0.01% | 0.01% | 0.0% | 0.0% | 0.0% |

Figure 5. Fiscal gas meters' size for gas transmission operators involved in the THOTH2 project: average values.

**Fig. 5.** Fiscal gas meters' size for gas transmission operators involved in the THOTH2 project: average values.

others remained unknown. Lastly, calibrated orifices can be realized by any technician based on the drawings of the orifice plate. Therefore, it was decided to not proceed into more details.

For distribution grids a different picture appears. Firstly, more than 115 million meters are installed in European distribution grids. Secondly, each European country is characterized by specific national rules, such as for example the adoption of the smart metering approach [90].

Unfortunately, the number of received answers does not allow us to report statistically significant results for the NG distribution grids. Only a preliminary draft can be discussed (Table 5). Regarding the performance indicator $n_{fgk}$, an average value of 65–75 m per km results from the received answers, i.e., a value quite near to the average value at the European level, which is 60 m/km (=115, 000, 000/2,000,000). The main fraction of meters is included in the G4-G6 size even though DSOs can operate a small fraction of larger size meters. In the received answers, meters greater than G65 were declared. No information was provided for process gas meters. However, the value is expected to be negligible compared to those installed for billing.

In terms of adopted technology, turbine and rotary piston gas meters are negligible, being limited to high-flow rate applications. On the other hand, diaphragm technology is the most implemented, followed by thermal gas meters and ultrasonic meters at low-flow rate. It has to be also highlighted that this scenario could be a consequence of the specific requirements adopted in each country. In fact, Gotze (2020) [91] reported that the 99.25% of the gas meters are diaphragm type in German distribution grids [46]. The remaining percentage is covered by the rotary piston (0.39%), turbine (0.32%), ultrasonic (0.02%), and Coriolis (0.01%) gas meters. Concerning gas market conditions, more than nineteen different manufacturers of gas meters were indicated in the portfolio of the answering DSOs. Of these, only one manufacturer was identified for the provision of thermal mass meters for distribution grids, resulting in a very critical element of the entire chain.

**Table 5**
Calculated performance indicators. for the analysed NG distribution grids.

| Symbol | Selected performance indicator | Value |
|---|---|---|
| $n_{fgk}$ | Number of fiscal gas meters per km of network | 65-75 [meters/km] |
| $n_{pgk}$ | Number of process gas meters per km of network | No information provided |
| $r_{pfg}$ | Ratio of fiscal and process gas meters | → 0 |
| $\chi_{fgt}$ | Fiscal gas meters' technology percentage ([a]) | Diaphragms: 1<br>Ultasonic[a]: 3<br>Thermal mass: 2<br>Turbine: limited applications<br>Rotary meters: limited applications |
| $\chi_{fgs}$ | Fiscal gas meters' technology per size penetration ([a]) | G4-G6: "1" Diaphrag[a], "2" Thermal mass; "3" Ultrasonic.<br>G10-G25: "1" Diaphragm; "2″ Thermal mass<br>G40: "1" Diaphragm; "2″ Rotary, "3" Turbine<br>≥G65: "1" Diaphragm; "2–3″ Turbine or Rotary |
| $N_{fgm}$ | Number of fiscal gas meters' manufacturers per technology | 19 |
| $N_{fgd}$ | Number of fiscal gas meters' models per technology | No detail provided |

[a] The number from 1 to 6 qualitatively indicate the penetration: 1 stands for the "most used"; "6" for the less.

### 3.2. Gas meters: technologies and hydrogen impact

In the next sections, the SoA of each gas meter technology, along with the impact of $H_2$ on each technology, is discussed, based on the information available in the literature and received from manufacturers [92].

#### 3.2.1. Turbine gas meters

Turbine gas meters consist of a bladed rotor that rotates due to the flow in the measuring chamber [93–96]. Greater velocity or pressure, or both, result in better metrological performances due to the increase of the driving force. The rotor movement is transferred to the shaft, which is supported by lubricated bearings within the measurement chamber, and to the counting mechanism (totaliser unit) for the measurement of the gas volume. Specifically, the rotor design is conceived to realize the minimum disturbances to the incurring flow. In the ideal case, the flow rate is proportional to the number of pulses. 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 [97–99].

Turbine gas meters are preferred for medium and high flow rate applications. From a constructive point of view, different materials are used depending on the nominal pressure (PN). Typical materials for the body are ductile iron or steel, even if hard anodized aluminium is used for low PN (up to PN16). The rotor is usually made of aluminium (usually for size larger than DN150), polyacetal-Delrin and less frequently stainless steel. Bearings and the main shaft are realized in stainless steel. A flow straightener is also positioned upstream of the rotor to minimize undesirable flow swirl and asymmetry when encountering the blades (typically 16, 20, or 24 blades are installed with an inclination equal to 30° or 45°).

*3.2.1.1. Hydrogen impact on turbine gas meters.* The literature review confirmed that the influence of $H_2$ on turbine gas meters is practically negligible at moderate amounts up to 10%vol $H_2$ in NG [25,100–104]. Furthermore, it was found that the response of the H2NG mixture was up to 30%vol at a pressure between 16 and 32 bar g is comparable to NG in Reynolds's domain. Increasing the $H_2$ amount would reduce the gas density and, potentially, the meters' measurement turndown (typically equal to 1:20 for NG at atmospheric pressure or higher at greater pressures), especially at the minimum flow rate ($Q_{min}$) [100,101,105,106]. In fact, reducing the gas density decreases the minimum flow rate by a factor equal to the square ratio between the reference and measured gas densities. Another concern in case of $H_2$ blending relates to overload operation resulting due to the increase of the volumetric flow rate.

Turbine gas meters are designed to allow overload operation for a short time. However, as reported by Gacek and Jaworski [80], no limit to the error of indication is given during overloading operations. Therefore, no conclusion can be made regarding metrological performances in the case of overload operation caused by $H_2$ injection.

While installation should be not affected by $H_2$ blending, potential impacts on ordinary maintenance have to be checked. Turbine gas meters are, in fact, designed for a lifespan of 25 years [107]. Typical activities include recalibration (at least every five years), bearings' lubrication, meters' inspection, and spin testing [108]. Since the gas mixtures come into contact with the oil, no specific indication was found in the literature about interactions. However, the compatibility should be checked with the manufacturers if not already stated in the available documentation.

Manufacturers reported a maximum $H_2$ content between 25%vol and 100%vol. It should be noted that these values may apply only for process purposes. For settlement purposes, the gas meter must have the approval of an EU Type Examination Certificate, which also confirms its capability to measure gas with the declared $H_2$ content. Some manufacturers already declared an EU-Type Examination certificate for 30% vol H2NG mixtures.

### 3.2.2. *Rotary piston gas meters*

Rotary piston gas meters have been well known since the beginning of the 20th century [109]. Rotary piston gas meters are usually preferred for low and medium flow rate applications in NG transmission and distribution sectors. The most common configuration includes two counter-rotating figure "8″ shaped rotors, i.e., the impellers [110,111]. However, the so-called "twin" configuration, which consists of two pairs of rotors shifted by 45° in the same body, can be adopted for high flow rates [112]. In this configuration, the pressure difference between the inlet and outlet imposes a force on the rotors, which are geared together through external synchronization gears. The measuring operation can be divided into four phases. A known gas volume enters the meter, and it is isolated between the lobes and the meter's body. In a second step the gas volume starts to move downstream following the rotation of the rotor, while the second rotor starts to trap another gas volume. In the third and fourth steps, the gas volume is discharged, and another volume is entrapped to start the cycle again. Therefore, four defined volumes of gas are moved during each complete rotation of the rotors. To date, cyclic volumes range between 0.25 $dm^3$ up to over 5 $dm^3$ resulting in rotational velocity of the rotors between 700 rpm and 5700 rpm.

From a constructive point of view, the body is made in aluminium or cast/ductile iron for medium-pressure applications (PN25/PN40), while steel is preferred for high-pressure applications (up to PN100). The measuring cartridge and the rotors are usually manufactured in aluminium. Due to the high velocity experienced by the moving parts, bearings and shafts are usually manufactured in stainless steel, such as other gas-wetted gears. However, Delrin and other synthetic materials can also be used.

To avoid excessive differential pressure and impeller wear, clearances are realized between the impellers and the body. Furthermore, the impellers don't touch each other while their phase relationship is maintained by spur gears on the impeller shafts. This design leads to a discrepancy between the actual displacement per revolution and the value measured, and results in a gas leakage through the clearance paths, the extent of which depends on the gas viscosity [113,114].

*3.2.2.1. Hydrogen impact on rotary piston gas meters.* The literature review confirmed that rotary gas meters can measure H2NG mixture up to 20%vol [25,102,103,115–118]. The main confirmation comes from the NewGasMet project [119] that found errors of indications within the MPE with a slight error shift (to negative errors). The NewGasMet project also confirmed through long-term tests that concentration of up to 20%vol $H_2$ does not affect the meters' operation. However, further investigation seems to be needed to check the material compatibility with higher concentration, as the effect of $H_2$ on aluminium alloys is not well understood in the literature [120–122], and a ductility loss seems to be induced in ductile cast iron [123–125]. In addition, other questions remain unsolved. For example, no public study was found about $H_2$ leakage. In fact, since the leakage is inversely proportional to the viscosity (10.9 μPa•s for NG and 8.8 μPa•s for $H_2$ at 20 °C) [111], known correlations seem to suggest an increase of it at higher $H_2$ concentration, resulting in a reduction of the meter's rangeability at $Q_{\min}$. Furthermore, no clear evidence about the effect of overload in the long-term is available. Therefore, no definitive conclusion can be drawn on this aspect at this time.

Regarding installation and maintenance, similar conclusions as those proposed for turbine gas meters are assumed. Specifically, rotary piston gas meters are designed for a lifespan of 25 years [107]. Maintenance activities include the correct lubrication of the rotor and of the timing gears during service. This involves inspecting the oil level every six months, or more frequently in the case of severe applications, and changing the oil after a scheduled period of service (usually between 5 and 8 years). Also in this case, the oil compatibility should be checked with the manufacturers if not already stated in the available documentation.

In addition to the information accessible in the literature, the contacted manufacturers assured that they have already conducted tests using H2NG mixtures and pure $H_2$. Specifically, they declared their models are allowed for concentrations up to 30%vol $H_2$. Most of the gas meters mentioned in the answers are declared to be useful for measuring 100%vol $H_2$. Therefore, from a technical point of view, gas meters can be used both for H2NG mixtures and pure $H_2$. However, compliance with ATmosphères EXplosibles (ATEX) requirements needs to be checked for the already installed meters.

### 3.2.3. *Ultrasonic gas meters*

Ultrasonic gas meters are installed both in NG distribution and transmission grids, which involve high flow rates. Ultrasonic gas meters adopt two measuring methods to calculate the volumetric flow rate, i.e., the time difference measurement (transit time), and the Doppler method [126–132]. In the "*transit time*" case, the measurand is the time, while in the Doppler method, the frequency shift. In "*transit time*" configuration the gas velocity is calculated by measuring the difference in transit times between two ultrasonic pulses emitted by transducers on the meter and travelling one parallel flow, the other counter flow. When no flow is present, the time difference is zero as the transit time of the pulses is inversely proportional to the speed of sound in the fluid. In the presence of flow, the ultrasonic pulses are accelerated when propagating in the same direction as the gas flow and decelerate when moving in the opposite direction. The greater the gas velocity, the larger the time difference measured. The meters based on "*Doppler effect*" operate on the principle of frequency or wavelength change of a wave in relation to an observer moving relative to its source. In this design, a pair of ultrasonic transducers is incorporated within the meter. One serves as a transmitter, emitting ultrasonic waves into the flowing gas, while the other as a receiver. As the ultrasonic waves travel through the gas, they encounter gas molecules. If the gas is moving, the motion of these molecules causes a shift in the frequency of the transmitted waves, known as the "*Doppler shift*".

From a constructive point of view, it is important to distinguish between inline and clamp-on configurations. In the inline configuration, the sensor is immersed in the fluid, while in the clamp-on configuration, the sensors are attached to the outside wall of the pipe. The inline configuration foresees the body realized in carbon steel or 316 stainless-steel, making possible to withstand very high pressure in transmission sector, e.g., up to PN 420, independently from the size (DN up to 1600). The transducers, consisting of a small piezoelectric ceramic disk, transmit and receive the sound wave at a frequency between 100 kHz and 300 kHz. Typically, frequencies above 200 kHz are selected as they are less affected by any noise in the system.

*3.2.3.1. Hydrogen impact on ultrasonic gas meters.* The first effect of $H_2$ blending would be an increase in the speed of sound. For example, an increase up to 12.3% occurs at 5%vol exceeding the threshold indicated in the ISO 14236, i.e., 475 m/s, for domestic gas meters [133]. On the other hand, from a technical point of view, the results of the SoA analysis are promising. Regarding metrological performances, experimental tests confirmed that ultrasonic gas meters maintain high measurement accuracy up to 10%vol [15,25,83,100,102–104,115,118,134–136]. Regarding materials, many types of carbon steel exist. Generally, $H_2$ degrades their ductility, reduces fracture toughness, and can be responsible for the acceleration of fatigue crack growth. However, there is no evidence yet to support any conclusions about the long-term behaviour of inline devices in presence of $H_2$. Conversely, material issues are not expected for clamp-on devices, as the sensors do not come into contact with the fluid. Regarding installation, similar conclusions to those for turbine and rotary gas meters are expected; a study [137] investigating by simulations the effect of $H_2$ concentration and of the distance of the meter from the NG and $H_2$ mixing point was found [138]. For maintenance, which typically includes annual checking of the contact between the transducer and the tube wall, assessing wall corrosion, and evaluating the status of the transducers, it cannot be determined yet if additional activities or an increase in frequency are necessary based on the current SoA regarding long-term behaviour.

Based on survey responses, a more promising picture appears for NG transmission meters. In fact, all the received answers confirmed the suitability of the devices for at least up to 30%vol $H_2$, with one manufacturer indicating that its meter had been successfully tested up to 100%vol. A similar conclusion was given for clamp-on ultrasonic gas meters, based on tests conducted and previous experiences in the refinery industry by the manufacturer. However, it is important to note that clamp-on devices are intended for process purposes and do not qualify for an EU-type approval certificate, making them unsuitable for fiscal purposes. A slightly different result was observed for domestic ultrasonic gas meters, for which the manufacturers confirmed the suitability up to 20%vol $H_2$, indicating that the main limitation to higher percentages refers to the ATEX compliance issue.

### 3.2.4. Diaphragm gas meters

Diaphragm gas meters are usually implemented in NG distribution or are limited to low-flow rate process purposes in the transmission sector [139–141]. Diaphragm gas meters measure the volumetric flow rate by passing the fluid through chambers with deformable walls. The principle involves isolating a known volume of gas in two measuring chambers during each measurement cycle. The size of each chamber corresponds to the measurement volume and is equal to a quarter of the cyclic volume [142]. The measurement process consists both in the continuous repetition of the operations of filling and emptying the chambers with gas and in taking into account the number of times this cyclic operation is performed [143]. From a constructive point of view, the gas meter is composed of i) a body containing the pressurized gas, ii) the diaphragms that move as gas pressure fluctuates on either side, iii) the valve covers and seats that regulate the gas flow into each side of the diaphragm, iv) the linkage to connect the diaphragm with the valves and index, and v) the components to account the gas volume like index drums [144]. In the past the membranes were typically made from animal skin, such as lambskin for small gauges and more resistant leather for medium-large gauges. However, synthetic materials, such as cotton or nylon, vulcanized with resistant rubbers (nitrile rubber, neoprene, Viton, or other types) are now the preferred choice. Over the years, other developments occurred allowing weight reduction, greater compactness, lower cost, and improved accuracy and stability [145].

*3.2.4.1. Hydrogen impact on diaphragm gas meters.* Because of their working principle, diaphragm gas meters are generally considered insensitive to gas composition. Many activities have been planned over the years to confirm this. The literature agrees that no effect is recognizable up to 10%vol $H_2$ in NG [16,26,100,102,104,146,147]. On the other hand, more ambiguous results were published at higher concentrations. For example, in the GHRYD project [101], where G4 and G65 m were tested to supply eighty houses and twenty apartments, a significant impact on metrological properties was observed at 20%vol $H_2$, by calculating an error in the range between −1% and 2.5%. However, this result was not confirmed by other publications that indicate a change in error within 0.3%–0.8% respect to the nominal use at flow rates below 0.1 $Q_{max}$ [16,27,102,117,118,146]. A greater $H_2$ percentage was tested by DBI-Gruppe. Testing G2.5-G6 meters up to 40%vol $H_2$, it was found that gas composition had a smaller impact compared to the presence or not of temperature-compensation. They found that the measuring deviations due to $H_2$ were comparatively small and were less than 1% at 40%vol [91]. To highlight the effect of $H_2$ on the gas meter durability, $H_2$ was added to assess the effects on leather and plastic components. The differences in meter readings using NG and the H2NG up to 17%vol, at five different flow rates ranging from 0.013 to 5 $m^3/h$ were checked. Given the calibration standards, which allow up to a 4% deviation for recalibration and expect repeatability within 0.2%, the measured differences were very small [148]. The study also looked at whether gas meters needed more capacity to measure mixtures of hydrogen and NG. The findings showed that, even with mixtures up to 17%vol, no more capacity would be needed.

Due to their operating principle, diaphragm gas meters are subject to ongoing safety considerations, particularly concerning leakage or permeation. To date, in fact, no general conclusion can be given since the $H_2$ compatibility respect to the membranes and other internal wetted parts largely depends on the materials implemented by each specific manufacturer [26,27,117,149–151]. Furthermore, current knowledge about the $H_2$ permeation through elastomers remains incomplete, requiring more experimental evidence to conclude about the potential impact of $H_2$ [120,152].

As for previous technologies, no evidence exists to support the assumption that changes are required to the existing rules about installation and ordinary maintenance. Concerning the increase of flow rate that occurs with $H_2$ blending, overload operation for short-term is ensured by this technology. However, this could be responsible of an increase of the noisy, and the frequency of filling and emptying of the diaphragms chamber that could deteriorate the meters in the long-term. Therefore, experimental evidence should check the need for larger meters.

As expected by analysing the literature, different conclusions appear from various surveys. Specifically, it can be concluded that $H_2$ impact is an individual matter for each specific model, and it depends on the technological solutions implemented. Two manufacturers declare the ability to measure pure $H_2$ without modification, but only one of them can support this claim with experimental results up to 100%vol $H_2$, while the other has completed the testing up to 30%vol. The publicly available results in the literature seem to confirm the conclusion.

### 3.2.5. Thermal mass gas meters

Thermal mass gas meters are well-proven devices that are installed both in distribution and transmission grids. Recent studies also confirmed their long-term stability after ten years of operation in the field [153]. The working principle of thermal mass gas meters is based on monitoring the cooling effect of the moving fluid on a heated element [154–156]. The electric power supplied to maintain the sensitive element 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 is used as a heater [157]. The heater can operate in two ways, e.g., constant current anemometer (CCA) and constant temperature anemometer (CTA). In the CCA configuration, the heater is kept 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 consequently, the more energy required to maintain the temperature difference. The mass flow rate is calculated by measuring the electric current supplied to the heater. This configuration is the most employed in industrial applications. In CTA devices the heater is powered with a constant electric current while the temperature difference is measured. In this case, the variation measured in the temperature difference is proportional to the mass flow rate change.

From a constructive point of view, the main components are described by Bekraoui & Hadjadj [154]. Focusing on transmission, two configurations exist, i.e., the inline and the insertion configurations. The capillary tube configuration is usually implemented in low-flow rate application [158]. The typical materials are aluminium for the transmitter enclosure, while the wetted components are usually realized in C-276, C-22 Hastelloy (a low-Fe containing Ni-base alloy), or stainless steel. Temperature sensor is usually a PT100 while the heating resistor is usually manufactured in platinum.

*3.2.5.1. Hydrogen impact on thermal mass gas meters.* Recently, there has been increasing attention given to thermal mass technology, with a specific focus on investigating metrological performances when altering the gas composition. Research already investigated the performances of thermal gas meters changing NG composition within the typical range of supply. For example, the research by Ficco et al. [159] and Parvizi et al. [160] provides relevant insights. For instance, Ficco et al. concluded that capillary types could assess the conveyed gas, and specific correction factors can be applied when the gas falls within the EN group H and the content of carbon dioxide and nitrogen is negligible [159]. On the other hand, the accuracy of the capillary configuration was found to be influenced by gas composition changes, and particularly the thermodynamic properties of the measured gas (such as viscosity, standard density, specific heat), especially when no compensation or correction was implemented. However, no tests were done for the other configuration, making it impossible to draw conclusions about the influence of gas composition. The literature indicates that these meters were successfully used to measure mixtures with up to 10%vol $H_2$ [27,102,104,118] even if Ficco et al. [161] were less confident the first generation of thermal mass meters for concentrations greater than 2%vol. based on experimental evidences. Therefore, it could be concluded that no uniform answer exists.

Regarding $H_2$ compatibility of the wetted materials, C-22 alloy shows a higher permeability compared with high-Fe alloys [162], and a potential impact on the tensile properties [120]. Hastelloy C-276, instead, is considered susceptible to $H_2$ embrittlement [163].

No sufficient evidence is available to conclude about the impact of H2NG on ordinary maintenance yet. For example, some devices are power supplied by a non-rechargeable battery. No data about the potential change of electricity consumption because of the changing of gas composition was found.

The responses obtained from the surveys distributed among manufacturers present a more promising picture of thermal mass meter technology. All industrial thermal gas meter manufacturers confirmed their devices' suitability for up to 100%vol $H_2$. However, only one model has EU-type approval and has been tested for the suitability of measuring pure hydrogen. Based on experimental testing, a manufacturer indicates that the measurement accuracy deteriorates with increasing $H_2$ concentration, starting from 10%vol.

Regarding domestic thermal mass meters, some models have EU-type approval for H2NG mixtures up to 2%vol. An unsatisfactory result came from testing the meter at 23%vol$H_2$ content since the manufacturer declared in the survey an error greater than that allowed in gas distribution application. However, dedicated models approved for H2NG with 23%vol and over 98%vol content are available.

### 3.2.6. Coriolis gas meters

Coriolis gas meters measure mass flow rate. Since their first use for custody transfer applications in 1995, Coriolis meters have proven to be a reliable way to measure NG flow rate [164,165]. The working principle is based on the well-known Coriolis force [166,167]. A centrally positioned device induces vibrations at the resonant frequency in the tubes containing the fluid. Due to the Coriolis force a phase shift in the oscillations of the tube occurs when a flow rate is passing though the meter. The pipe oscillation, detected by electrodynamic sensors, is no longer symmetrical with respect to the centreline and increases with the flow rate. This is justified by the Coriolis force that induces a deceleration of the oscillation at the inlet of the tube and an acceleration at the outlet. In contrast, when no flow rate is present, the tube oscillates in phase, meaning the displacements are symmetrical.

Focusing on the design, Coriolis gas meters consist of two main components: a sensor (the primary element) and a transmitter (the secondary element). The sensor design varies significantly among manufacturers, leading to several configurations on the market, such as single and dual tubes, among others, designed to minimize external disturbances [168,169].

*3.2.6.1. Hydrogen impact on Coriolis gas meters.* Numerous studies have investigated the performance of $H_2$ Coriolis meters, especially for $H_2$ refuelling applications, which involve pressures higher than in NG grids. These studies have focused on metrological performances and behaviour in transient flows [170–173]. However, only a few experimental studies on H2NG mixtures were found in the literature. Nevertheless, it can be concluded that Coriolis flow meters can be safely applied to H2NG with up to 10%vol [102–104,135]. Moreover, Coriolis flow meters were found to perform well up to 30%vol and 16–32 bara providing adequate compensation for pressure and sound velocity effects [118].

As demonstrated by the aforementioned tests and based on the extensive experience of the gas meter and flowmeter testing laboratory staff, it can be concluded that Coriolis flowmeters are suitable for use with up to 100%vol. This conclusion is further confirmed by the response given by a manufacturer who declared the capability of its meters to handle varying $H_2$ percentages (up to 30%vol) and even pure $H_2$. This behaviour is justified because of the technology is able to detect the variation of the fluid composition through the vibration frequency, that is proportional to the medium density. This peculiarity makes Coriolis meters a good choice for applications where gas composition and density are expected to change during operation [165]. However, small size meters are not well suited for low mass and high-volume applications since they show insufficient sensitivity [174].

Special cares have to be considered when handling $H_2$ to minimized leakages especially in the selection of the materials such as the connections to the process, due to the risk of $H_2$ embrittlement [175]. No evidence in the literature indicates effect of $H_2$ on those components not in contact with $H_2$. The impact of $H_2$ is assumed to be on those components in contact with $H_2$, such as the sensors and other measuring devices installed within the meter. Based on the review of commercial devices' datasheets, 304 L, 316/316 L, 904 L, and Hastelloy C22 are typically used. In contact with $H_2$, 316 stainless steel alloys show a modest reduction in ductility and an increase in strength maximized in case of 316 L that is characterized by the lowest content of nickel (Ni) [176]. This conclusion is confirmed by other authors that found that austenitic steels with a Ni content higher than 7% are considered suitable to be used in applications with $H_2$ [177,178]. Conversely, 304 stainless steels show a high susceptibility to the $H_2$-induced embrittlement and cracking [120,179,180]. Limited data are available for 904 L. For example, Michalska et al. [181] suggested that the stress-strain relationship is not influenced by $H_2$ to the point of causing a significant modification of the yielding point [141].

As with other technologies, no conclusions can be inferred about installation and maintenance based on the currently available SoA information.

### *3.2.7. Calibrated orifices*

Orifice plates are pressure differential devices and invasive instruments [182–188]. They are well known measuring devices with decades of operation in NG sectors thanks to their relatively low cost, the absence of moving parts and no limits on temperature, pressure and size. Typically, they are used for process purposes by gas operators. In fact, their accuracy typically ranges between 0.6 and 2% [189] with a rangeability from 1:3 to 1:7 [80]. However, bad performances can occur due to the presence of disturbance elements, eccentricity of the plate, internal pipe roughness, and incorrect calibration of the differential pressure measuring devices [190].

The calibrated orifice (or orifice plate) simply induces a concentrated pressure drop that is proportional to the square of the gas velocity based on Bernoulli equation. The fluid velocity is calculated by measuring this pressure drop, while the mass flow rate is derived in accordance with the correlations outlined in the technical standards, i.e., EN ISO 5167–1 and EN ISO 5167–2 [191,192]. These standards include the calculation of the discharge coefficient using the Reader-Harris/Gallagher method [193].

From a constructive point of view, both the design and realization of meters (i.e., the respect of the roughness) are very important since any deviation would lead to changes in the discharge coefficient, and consequently, to measurement errors. Furthermore, incorrect data about the diameter of the upstream tube and of the orifice bore can also produce errors [194]. In terms of design, both single-hole and multi-hole orifice configurations are used [193,195,196]. While the single-hole design is simpler, the multi-hole configuration ensures a more uniform distribution of flow field parameters near the plate across the entire pipe cross-section, improving metrological performance. The plates can be

**Table 6**

Metrological performances of commercial gas meters installed in state-of-the-art NG grids.

| | Turbine gas meters | Rotary piston | Ultrasonic | Diaphragm | Thermal mass | Coriolis | Calibrated orifice |
|---|---|---|---|---|---|---|---|
| **Reference standard** | ISO 12261–2018 [197] | EN 12480:2018 [198] | ISO 17089–1:2019;<br>ISO 17089–2:2012 [199,200];<br>EN 14236:2018 [133] | EN 1359:2017 [201] | EN 17526:2021 [202] | ISO 10790:2015 | ISO 5167–1:2022<br>ISO 5167–2:2022 [191,192] |
| **Sector** | Transmission<br>Distribution (limited) | Transmission<br>Distribution (limited) | Transmission<br>Distribution | Transmission (limited)<br>Distribution<br>Limited to pressure up to 500 mbarg | Transmission (limited)<br>Distribution | Transmission (limited) | Transmission (limited) |
| **Size range** | Up to G16000 (25.000 $m^3/h$) | Up to G1000 (1600 $m^3/h$) | Up to 120.000 $m^3/h$ or DN1400 (56″) | Up to G100 (160 $m^3/h$) | Up to 6240 Nm3/h | Order of hundred thousand of kg/h | Ideally no limits |
| **Applications** | Fiscal and process | Fiscal and process | Fiscal and process | Fiscal | Process<br>Fiscal (only distribution) | Fiscal and process | Only Process |
| **Turndown** | 1:20 at atm. pressure<br>Up to 1:30/1:50 by increasing pressure | 1:160 | 1:150 (Inline configuration) | 1:160 | up to 1:100 (standard)<br>1:1000 (special) | >1:500 | 1:3 to 1:10 |
| **Linearity** | Based on pressure and diameter as per ISO 12261–2018 | Not indicated | Not indicated | Not indicated | Not indicated | Not indicated | Not indicated |
| **Repeatability** | 0.1% or better | 0.1% or better | ±0.05%–0.1% (Inline configuration)<br>±0.15% (clamp-on) | $Q_t \leq Q \leq Q_{max}$ 0,6% | $Q_{min} \leq Q \leq Q_t$ 1.0%<br>$Q_t \leq Q \leq Q_{max}$ 0,6% | ±0.25% | Not indicated |
| **Stability** | Good performance [203–205] | Not indicated | Not indicated | Not very good for a single meter [206] | Not indicated | Not indicated | Not indicated |
| **Pressure drops (*)** | 5–20 mbar | <10 mbar | acc. EN 14236 2.0 mbar | <2.0 mbar<br>Pressure pulsation investigated in [143] | 1–2 mbar | Depending on the meter size, maximum mass flow rate and density of gas. High pressure drops more than 5 bar. | Is the design parameter of the meter |
| **Flow variations/ intermittent flow** | Problems due to its inertia [80, 207–209] | No problems | Inadequate sampling time could be responsible for errors | No problems | The response time plays a key role in accurately measuring unsteady flow [210] | No particular issues | No particular issues, provided the measurement of differential pressure is accurate/reliable enough |
| **Overload** | Up to 120% for 1 h as per ISO 12261<br>Higher values are also available | Up to 120% for 0.5 h as per EN 12480<br>Higher values are also available | Errors of indication at 120% | Up to 120% for 1 h as per EN 1359 | Up to 120% for 20 min | – | No specific issues.<br>Higher pressure drop |

Pressure drops: Pressure drops are measured 1DN upstream and 1DN downstream of the meter, using atmospheric air as the test medium. The values reported are based on the datasheets of the models installed in THOTH2 project partners' grids, assuming NG as a medium with a density of 0.8 $kg/m^3$.

**Table 7**
Design characteristics of gas meters installed in NG grids.

| | Turbine gas meters | Rotary piston | Ultrasonic | Diaphragm | Thermal mass | Coriolis | Calibrated orifice |
|---|---|---|---|---|---|---|---|
| **Pressure rating** | Up to PN100 | Up to PN100 | PN420 (Transmission)<br>Up to 0.5 bar g (Distribution) | Up to 0.5 bar g | Up to PN40 (Transmission)<br>Up to 0.5 bar g (Distribution) | As a function of the DN. Up to 400 bar | Not applicable |
| **Length** | Down to 2DN | – | Down to 3DN | – | – | – | – |
| **Main components** | Body, flow straightener, rotor, bearings and shaft | Body, measuring cartridge and rotor | Body, transducers, the electronics, the data processing and presentation unit | Enclosure and membranes | Body and temperature sensors | Body, sensor and the transmitter | Orifice plate |
| **Materials** | Body:<br>Ductile iron and steel (high pressure); hard anodized aluminium (low pressure, i.e., up to 16 bar g)<br>Rotor: Aluminium (usually for size larger than DN150), polyacetal-Delrin, and, less frequently, stainless steel<br>Bearing and main shaft: stainless steel | Body:<br>Aluminium or cast/ductile iron (medium pressure up to PN25/PN40); steel (high-pressure, i.e., up to PN100)<br>Rotor: aluminium<br>Bearings and main shaft: stainless steel | Body:<br>Carbon steel and 316 stainless.<br>Transducers: included in an arrangement of metal parts and high-grade epoxy within a titanium housing. | Enclosure: steel<br>Membranes: synthetic materials, such as cotton or nylon, and vulcanized with resistant rubbers. | Body:<br>Aluminium.<br>Wetted components: C-276, C-22, Hastelloy and stainless steel<br>Temperature sensors: Pt100<br>Heating resistor: platinum | 304 and 316 L Stainless steel | Stainless steel is the typical material even if any material can be used |

made of any materials [192]. However, American Iron and Steel Institute (AISI) 316/316 L are typically used in NG sector applications.

*3.2.7.1. Hydrogen impact on calibrated orifice plates.* To convey the same amount of energy, $H_2$ blending would result in higher volumetric flow rate caused by the reduction of the gas mixture density. Therefore, the concentrated pressure drops, i.e., the energy losses, would increase with the $H_2$ concentration in the mixtures. Consequently, the upper range limit of the installed differential pressure transmitter has to be verified with the changed range to check the pressure drops variation, i.e., if a new plate would be needed. Regarding materials and plates, as reported for Coriolis meters, no particular limitations seem to apply when using 316 and 316 L stainless steel.

A critical issue could arise in case of unsteady $H_2$ concentration. In this case, the flow computer would require additional information beyond mixture temperature and pressure to calculate the gas mass flow rate. A gas quality analyser able to measure $H_2$ concentration would be therefore necessary.

No metrological degradation due to contamination is expected from the $H_2$ injection. In fact, H2 filtering will be required before the injection into the NG grids. However, in the case of compression, the convey of oil droplets resulting from compression resulting in fouling needs to be carefully assessed.

As with other technologies, no other conclusions can be drawn about installation and maintenance based on the currently available SoA information.

### 3.2.8. *Synthesis of the key findings*

The main SoA data for each technology are reported in Table 6 (Metrological performances of commercial gas meters installed in state-of-the-art NG grids), Table 7 (Design characteristics of gas meters installed in NG grids), Table 8 (Main requirements about installation and ordinary maintenance of gas meters in NG grids) and Table 9 (Impact of $H_2$ in state-of-the-art gas meter: a summary). Table 6 presents a detailed comparison of the metrological performances of various commercial gas meters used in SoA natural gas (NG) grids, covering a range of technologies from turbine and rotary pistons to ultrasonic and Coriolis meters. Each meter type is aligned with specific international standards, such as ISO and EN, ensuring their reliability and accuracy for designated applications in transmission and distribution sectors. The table categorizes these meters based on key performance metrics like turndown ratio, linearity, repeatability, and pressure drops, offering a comprehensive view of their operational capabilities. Table 7 provides a detailed overview of the design characteristics of various types of gas meters installed in NG grids. This information is useful for understanding the technical specifications and suitability of each meter type for different applications within NG grids. Table 8 offers a comprehensive examination of the main requirements for the installation and routine maintenance of various gas meters utilized in NG grids. Table 8 also provides valuable insights into the expected lifespan of each meter type, the frequency and nature of required maintenance activities, and potential causes of failure. Table 9 provides an overview of the impacts of $H_2$ on each technology.

## 4. Discussion

### 4.1. *Identified gaps and barriers*

Different scenarios characterise gas metering plants in transmission and distribution networks. In high-pressure and high-flow-rate grids, the turbine gas meter is the prevalent technology, followed by ultrasonic and rotary-piston gas meter technologies. In distribution grids, on the other hand, diaphragm gas meters are the most commonly installed, although other technologies like ultrasonic and thermal mass gas meters are beginning to penetrate the market, thanks to advantages such as the

**Table 8**

Main requirements about installation and ordinary maintenance of gas meters in NG grids.

| | Turbine gas meters | Rotary piston | Ultrasonic | Diaphragm | Thermal mass | Coriolis | Calibrated orifice |
|---|---|---|---|---|---|---|---|
| **Installation** | | | | | | | |
| **Orientation requirement** | Vertical and horizontal installation allowed | Shaft horizontal for correct lubrication | No specific requirement | Vertical only | No specific requirement | Horizontal up and flag positions are common | – |
| **Straight pipe required upstream and downstream** | Yes.<br>Upstream: 2DN - 5DN<br>Downstream: up to 3DN | No | Yes.<br>Upstream: at least 5DN<br>Downstream: at least 3DN | No | Yes. | Straight-tube full bore meters are more susceptible to upstream obstacles compared to twin-tube design [211] | Specific requirements are indicated by ISO 5167–2. |
| **Additional components** | An upstream filter could be required | An upstream filter could be required | A flow conditioner could be required | No | A flow conditioner can be installed to reduce the fluid-dynamic disturbances | | No |
| **Other relevant info** | Turbine meter's length can be reduced down to 2DN | – | Ultrasonic meter's length can be reduced down to 3DN. Attention when installed near to pressure regulation station since the pulsating sound waves can affect the measure | No | – | Proper piping alignment without rotational torque or mechanical binding is crucial for accurate meter performance | – |
| **Ordinary maintenance** | | | | | | | |
| **Life Span** [107, 153] | 25 years | 25 years | 15 years | 25 years | 20 years | 10 years | 30 years |
| **Yearly maintenance** | Lubrication (1–6 months based on application)<br>Internal inspection; spin testing.<br>Calibration in the laboratory (usually every 5–6 years) | Correct lubrication of the rotor and the timing gears<br>Calibration every 5 years | Diagnostics (1 per year)<br>Check for internal corrosion<br>Cleaning in the case of contamination growth<br>Verification of transducers<br>Calibration in the laboratory (usually every 5–6 years) | Recalibration and if necessary adjusting each 10 years | Annual checks of the measuring devices<br>Calibration every 5 years | Verification of the correct operation of the transmitter, sensors and "zero" measurement condition<br>Calibration each 5 years | Verification of the orifice plate bore size and visual examination of the plate [212].<br>Annual calibration of the pressure differential transmitters.<br>Calibration every 5 years |
| **Extraordinary maintenance** | | | | | | | |
| **Potential cause of failure** | Breaking of blade rotor or bearings or pulse pick-offs (between normal maintenance periods.<br>Pulsating/on-off flow disorders. | Jamming of rotors by contaminants, which will block the flow. May generate resonance. | Extraordinary dirt or liquids inside USM (detected by diagnostic parameters supervision), may force to remove USM and send it to laboratory. | Internal leakage of the measurement system due to extreme temperatures.<br>Contaminants in the gas stream, such as dirt, debris, or moisture, can affect the diaphragm's movement and lead to meter failure.<br>Improper installation, including misalignment, incorrect pipe sizes, or inadequate support, can lead to operational issues. | Extraordinary contaminants of gas (dust or oil), may force to remove thermal mass gas meter and send it to laboratory or service | Physical damage to the meter, such as impact or excessive vibration, can lead to mechanical failure.<br>Contaminants in the gas stream, such as dirt, debris, or corrosive substances, can affect the meter's performance.<br>Over time, materials in the meter may experience fatigue due to cyclic stresses, leading to potential failure. | Exposure to corrosive gases or environmental conditions may lead to the degradation of materials in the meter. |

**Table 9**
Impact of $H_2$ from the SoA of gas flow meters: a summary.

| Turbine gas meters | Rotary piston | Ultrasonic | Diaphragm | Thermal mass | Coriolis | Calibrated orifice |
|---|---|---|---|---|---|---|
| A lack of standardized protocols and testing facilities with the capability to conduct tests with H2NG mixtures and pure $H_2$ at high pressure is common to all technologies<br>Lack of a clear pathway for certifying measuring devices especially regarding ATEX.<br>The presence of the EU Type Examination Certificate is still missed in many models | | | | | | |
| *Metrological performances (below)* | | | | | | |
| Potential reduction of the rangeability due to the change of the gas density<br>No information about accuracy during overload operation | Theoretically, due to the working principle, these meters are generally insensitive to the gas composition.<br>Potential reduction of the rangeability due to the increase of $H_2$ leakages | Results at the SoA are promising even if a change in the Speed of Sound of the medium occurred. | Positive tests up to 40%vol. | The literature indicates that these meters were successfully used to measure mixtures with up to 10%vol. | Tests on Coriolis flowmeters show that the technology perform well up to 30%vol. and 16–32 bara providing adequate compensation for pressure and sound velocity effect | Since the gas density is considered in the algorithm, any change has to be carefully measured and provided to the Flow Computer for accurate calculation. |
| *Manufacturers' feedback (below)* | | | | | | |
| Manufacturers declared maximum $_{H2}$ content from 25%vol to even 100%vol. | Manufacturers declared the suitability up to 30% vol.<br>Some models up to 100%vol. | Manufacturers confirmed the suitability of the devices by at least up to 30%vol.<br>A model already positively tested up to 100%vol.<br>However, products dedicated to distribution can be limited to 20%vol due to ATEX compliance. | Some manufacturers declare the ability to measure also pure $H_2$ without modification. | Based on experimental testing, a manufacturer indicates that the measurement accuracy deteriorates with increasing $H_2$ concentration, starting from 10%vol. | Manufacturers declared the capacity of handling H2NG up to 30%vol. or pure $H_2$. | No specific indication |

absence of moving parts. Since a lot of models provided by different manufacturers are currently installed in the grids, no overall conclusion can be provided about $H_2$ suitability. Several gaps and barriers have been identified among the SoA gas meters that are currently operated in NG transmission and distribution networks, as summarized in Table 9.

First of all, SoA information regarding the potential technological issues provided only preliminary indications. More tests are needed to confirm the performances of the specific models or to provide any evidence about the need to review the related technical standards. The barriers mainly include the lack of standardized testing protocols and facilities capable of handling H2NG mixtures at high-pressures and flow rates. Only a few test benches are available to validate the performances of the gas meters with H2NG mixtures, especially for the simulation of transmission operating conditions.

There are two possibilities to address this gap: building new infrastructure or revamping existing test benches. As noted by Turkowski et al. [213], a high-pressure gas meter calibration facility is a complex plant that can operate in either an open-loop configuration, connected to the NG transmission grid, or in a closed-loop configuration, recirculating the fluid using a dedicated blower [173]. Large amounts of $H_2$ are required for comprehensive testing activities, especially for high-flow rate testing. Re-injecting the fluid into the gas grid, as in the open-loop configuration, could be hindered or limited by current regulations regarding $H_2$ limits in the grid [164].

The impact of $H_2$ blending on gas meters has to be carefully verified. The certification pathways for existing gas meters with H2NG mixtures, particularly regarding ATEX compliance, are unclear, complicating the certification process. There may be a need to replace existing components based on their ATEX certification, as the fluid classification changes from IIA group for H2NG mixtures up to 25%vol, to IIB between 25%vol and 75%vol, and to IIC group for higher concentrations [214–216]. There is a lack of a clear pathway regarding the need to certify devices currently installed in the grid for contact with a fluid classified under a different ATEX group. Comprehensive ageing tests are required to certify long-term performance under H2NG conditions. The infrastructure for testing gas meters under realistic operating conditions with H2NG mixtures needs development or revamping, as current facilities may not adequately simulate operational environments. Feedback from manufacturers indicates varying levels of suitability for different gas meter technologies, highlighting the need for more consistent and reliable data. Even if manufacturers confirm the suitability of a specific product for operation with an H2NG mixture, there are no current rules indicating how to re-certify measuring devices that have been in operation for many years in the field.

Thirdly, confirmation of metrological and safety performances is required to support social acceptance. Ageing tests are essential to certify that no long-term degradation occurs. While the tests could be performed in the laboratory for domestic gas meters (<G65), the transmission gas meters would be more complicated to test, especially in the case of dynamic tests. Static tests can provide preliminary indications about the potential issues, but dynamic tests are necessary to provide concrete evidence of any changes that could occur in the field.

### 4.2. *Hydrogen tolerance of gas meters: which effect on sector coupling in the short-medium term?*

As indicated in Pellegrini et al. [217], the capability of the existing NG grids to accommodate renewable $H_2$ depends both on the tolerance of the components installed and on the compatibility of the end-users. Focusing to the topic of the paper, as shown in previous sections, the installed gas meters are characterized by specific $H_2$ thresholds. As proposed by Cavana & Leone [218] for biogas blending in gas grids [178], a maximum amount of $H_2$ will be injectable in the grid depending on external factors such as, for example, the real time gas flow rate, i.e., the demand supplied by the grid. For example, Ekhtiari et al. [219] found that a $H_2$ content up to 15.8%vol can occur in the Irish transmission networks by converting wind energy into $H_2$ avoiding renewable curtailment [179]. Focusing on the Italian gas transmission grid, Jin et al. [220] indicated that increasing the $H_2$ blend up to 20%vol would require an increase of the conveyed NG affecting the complexity of managing grid operation [180]. A recent analysis published by Bart et al. [104] indicated that a blending ratio of 5%vol would consume almost 40% of the renewable $H_2$ supply from the 40 GW water electrolyser target. They also concluded that the value would increase up to 20%vol if the 90% of produced $H_2$ was injected into the grids. Since $H_2$ injection fluctuation were not considered in their study, it is clear the need to verify SoA gas meters' performance at increasing $H_2$ percentages up to at least 25%vol, i.e., the threshold above which the ATEX certification changes.

Economic impacts on the existing infrastructure due to $H_2$ blending or pure $H_2$ transport should be carefully assessed to ensure proper budget allocation by gas system operators. Marcogaz, the European gas system operators' sector association, provided preliminary estimates in two public reports published in 2023 [221,222]. For example, although they are minor components of the grids, the transformation cost for metering stations in European transmission gas grids is estimated to exceed 0.14 billion euros for $H_2$ concentrations greater than 10% vol. For distribution assets, even if the input data are limited to German case and to diaphragm meters [221], transformation costs are indicated only for percentages greater than 20%vol. The total transformation cost of more than 9700 million euros is reported. However, even though the economic values indicated in the reports provide preliminary estimates, the assumptions underlying these calculations could contribute to significant economic uncertainty.

The identification of the $H_2$ limits of the installed gas meters or of any other equipment installed in the grid is necessary to properly manage $H_2$ injections in the grid until the retrofit of the grid to pure $H_2$ will be completed. Since renewable $H_2$ production is not totally forecastable or predictable [223], the NG and $H_2$ streams entering and exiting the grids should be managed to minimize renewable energy curtailment occurring in the case that H2 limits would be exceeded. Projects like THOTH2 and other ones such as, for example SHIMMER (SHIMMER: *Safe Hydrogen Injection Modelling and Management for European gas network Resilience*) project (focusing on NG grids' fluid-dynamics simulation) [224] and PNRR-NEST-SPOKE 4 and SPOKE 7 (*Network for Energy Sustainable Transition – Spoke 4: Clean hydrogen and final uses; Spoke 7 – Smart sector integration*) project (focusing on the development of models and digital twin of renewable and power to gas plants) [225], will provide operators all the resource to optimally manage their grids and success the energy transition target.

## 5. Conclusions and follow-up actions

The transport of pure $H_2$ or H2NG mixtures in existing gas infrastructure is considered a valuable opportunity to energy system decarbonisation. Gas meters are essential components of gas networks covering different purposes, including gas billing, process control, and monitoring the energy flow through the grids. H2 blending or transport into the existing NG infrastructure could potentially affect tens of thousands and millions of devices installed in European gas transmission and distribution grids, respectively.

By analysing the gas meters installed in EU NG grids, the present study found that.

- Transmission NG grids:
    - About 0.11–0.35 m per km result installed in the investigated NG grids.
    - Regarding the technology installed in gas transmission grids, turbine gas meters are the most implemented followed by rotary and ultrasonic gas meters. Only one operator declares a relatively high number of gas diaphragm meters, while other technologies, like Coriolis meters have not penetrated the market yet.
    - Regarding the size, more than 60% of the total devices have a size between G250 and G1600.
- Distribution NG grids:
    - More than 115 million of meters are installed in EU distribution grids but each country adopts national rules.
    - About 65–75 m per km can be assumed installed in the investigated NG grids.
    - The most implemented technology is diaphragm type followed by ultrasonic, and thermal mass. Turbine and rotary types have been identified but limited to few applications in distribution cases.
    - Most of the meters are G4 or G6.

The information available in the literature and confirmed by manufacturers creates confidence in the technical capability of the meters to handle H2NG mixtures. Due to the wide variety of manufacturers and models available in the market, with varying design and material specifications, it is not possible to provide a definitive conclusion on $H_2$ compatibility even if preliminary considerations are possible for the most implemented technologies. In fact, the literature review and the manufacturers' survey allow to state.

- Turbine gas meters: no influence appears up to 10%vol. For greater concentrations, the literature shows promising results up to 30%vol at pressure between 16 and 32 bar g that are confirmed also by the contacted manufacturers.
- Rotary piston gas meters: the literature reports positive evidences up to 20%vol. even if the manufacturers also indicated greater concentration up to 30%vol. or 100%vol. However, the effect of leakage through the clearances on rangeability has to be investigated.
- Ultrasonic gas meters: as for rotary type, ultrasonic gas meters for transmission networks are confirmed up to 100%vol. by some of the contacted manufacturers. However, the literature indicates evidences of the performances up to 20%vol. In the case of domestic application, however, limitation occurs at normative level due to limitation of the speed of sound. Furthermore, the contacted manufacturers declare their products up to 20%vol.
- Diaphragm gas meters: the literature presents different tests of this gas technology at different concentration up to 40%vol. However, $H_2$ molecules permeation through the membrane is still an open question. From a market point of view, the majority of answers from manufacturers indicate devices able to measure up to 30%vol., even if some tests have been performed up to 100%vol. by one of the participants to the survey.
- Thermal mass meters: literature indicates that this technology can be used up to 10%vol. even if older models give unsatisfactory results already above 2%vol. Regarding domestic market, manufacturers declared an error greater than that allowed in gas distribution application. However, models approved for H2NG with 23%vol. and over 98%vol. are available.

While the results of the study are limited to THOTH2 partners' gas grids, they allow to provide recommendations on how to go beyond the SoA and the topics that research needs to address, including ageing tests, to confirm the metrological performances and the material compatibility under various operative conditions. For this purpose, the following actions are recommended.

- To provide a priority ranking about the gas meters to be tested based on the numbers and percentage of installed devices and the knowledge about their readiness.
- To define a rigorous methodology to test gas meters with $H_2$ or H2NG and a way for extrapolating results to other ranges or to consider using different fluids capable of simulating the fluid dynamic behaviour of the gas medium.
- To estimate the economic impact of gas meters substitution in the case that experimental evidences confirm their unavailability in case of $H_2$ injection.

Nevertheless, addressing gas meters' technological barriers alone will not be sufficient if regulatory aspects are not discussed and addressed. Specifically, ATEX certification is of paramount importance. New components will be designed and introduced into the market with the proper certification; all the involved stakeholders, including technical and jurisdictional experts, need to define how to manage the certification of devices that have already been installed.

## CRediT authorship contribution statement

**Alessandro Guzzini:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Marco Pellegrini:** Writing – review & editing, Visualization, Investigation, Formal analysis, Data curation. **Cesare Saccani:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Adrian Dudek:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Monika Gajec:** Writing – review & editing. **Anna Król:** Writing – review & editing. **Pawel Kulaga:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **Paola Gislon:** Writing – review & editing. **Viviana Cigolotti:** Writing – review & editing. **Matteo Robino:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Diana Enescu:** Writing – review & editing, Writing – original draft, Conceptualization. **Vito Claudio Fernicola:** Writing – review & editing. **Denis Smorgon:** Writing – review & editing. **Remy Maury:** Writing – review & editing. **Andrea Gaiardo:** Writing – review & editing. **Matteo Valt:** Writing – review & editing. **Dorota Polak:** Writing – review & editing. **Hugo Bissig:** Writing – review & editing.

## Declaration of competing interest

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

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