International Journal of Hydrogen Energy 67 (2024) 1295–1307

Contents lists available at ScienceDirect

International Journal of Hydrogen Energy

journal homepage: www.elsevier.com/locate/he

Hydrogen blending effect on fiscal and metrological instrumentation: A review

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ARTICLE INFO

Handling Editor: Ramazan Solmaz

Keywords:
Hydrogen
Hydrogen/natural gas mixtures
Hydrogen blending
Natural gas measuring devices
Natural gas metrology standardisation and normative

ABSTRACT

A green hydrogen (H_2) economy requires a sustainable, efficient, safe, and widespread infrastructure for transporting and distributing H_2 from production to consumption sites. Transporting a hydrogen/natural gas (H2NG) mixture, including pure H_2, through the existing European natural gas (NG) infrastructure is considered a cost-effective solution, particularly in the transitional phase. Several reasons justify the H2NG blending option. The NG infrastructure can be efficiently repurposed to transport H_2, by blending H_2 with NG, to operate as H_2 daily storage, matching production and demand and to enable large-scale seasonal H_2 storage. Although many benefits exist, the potential of existing NG grids for transporting and distributing green H_2 may face limitations due to technical, economic, or normative concerns. This paper focuses on the state of the art of the European NG transmission and distribution metrology normative framework and identifies the gaps to be filled in case of H2NG flowing into the existing grids. The paper was revised to provide a comprehensive analysis of the practical implications resulting from the H2NG blend option.

1. Introduction

As a consequence of the gas energy crisis and the need to achieve decarbonization targets, the RePowerEU plan has been adopted, aiming to boost the green hydrogen (H_2) market by setting new targets for 2030. The plan aims to produce at least 20 million tons of green H_2, with half of it coming from imports outside of Europe. Despite the production mode [1–4], to facilitate the transportation and distribution of such a large volume of H_2 and make it feasible for the energy transition [5], the existing natural gas (NG) grid is considered a competitive option compared to other alternatives, such as transport by truck or conversion into e-fuels.

While the transportation of H_2 in dedicated networks across countries, i.e., the European H_2 backbone initiative, is more realistic in the long-term solution [6], the injection of H_2 into the existing NG grid is recognized as a suitable "first step" to accommodate a greater amount of renewable H_2, thereby also supporting renewable dispatchability [7]. The interest in H_2 blending has been confirmed by many contributions from different stakeholders of the energy sector in recent years [7–16]. Dolci et al. (2019) first reported the legal barriers against H_2 blending in European countries [17]. Moreover, several countries including, for example, Italy [18], France [19], Germany [20], Poland [21], Spain [22], the Netherlands [23], and the United Kingdom [24], indicated their interest in blending H_2 into NG grids as a potential option to transport renewable H_2 and to sustain market uptake in a transitional phase, as also reported in the European H_2 strategy [25]. The Joint Research Centre (JRC) study by Kanellopoulos et al. (2022) also focused

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https://doi.org/10.1016/j.ijhydene.2024.02.227
Received 7 December 2023; Received in revised form 11 February 2024; Accepted 16 February 2024
Available online 2 March 2024

List of acronyms and symbols

ATEX	Atmosphères Explosibles
CAPEX	Capital Expenditure
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
CH_4	Methane
CLC	CENELEC National Committees
CO_2	Carbon dioxide
DSO	Distribution System Operator
GIE	Gas Infrastructure Europe
H_2	Hydrogen
He	Helium
HHV	Higher Heating Value
H2NG	Hydrogen added natural gas (hydrogen content in natural gas: [0,100] %vol.)
ISO	International Organization for Standardization
IW	Wobbe Index
JRC	Joint Research Centre
JTC	Joint Technical Committee
LPG	Liquefied Petroleum Gas
MID	Measuring Instruments Directive
MPE	Maximum Permissible Error
N_2	Nitrogen
NG	Natural Gas
O_2	Oxygen
RCS	Regulations, Codes and Standards
SoA	State of Art
TC	Technical Committee
TSO	Transmission System Operator
Z	Compressibility factor
WG	Working Group

the research to assess the consequences of H_2 blending for NG systems [26].

Several reasons justify the hydrogen/natural gas (H2NG) blending option, even if some gaps still exist [27,28]. With limited investment, the NG infrastructure can be repurposed efficiently for the transportation of H_2, whether blended with NG or in its pure form, contributing to renewable energy storage and grid balancing when a surplus of renewable energy is produced [29,30]. In recent years, several European entities, including the European Commission and the European Parliament, along with the Council, have taken significant steps towards implementing H2NG blending programs. The European Commission, recognising the potential of H_2 in achieving climate neutrality, launched a comprehensive H_2 strategy in 2020. This strategy encompasses actions for mainstreaming clean H_2 and integrating renewable H_2 electrolysers, with some EU countries setting specific blending targets for 2030. This reflects the Commission's commitment to decarbonising NG and incorporating H_2 into the existing NG grid [25]. Although the NG infrastructure can be repurposed for the transportation of H_2 once blended with NG, it is still not clear yet whether the transport of pure H_2 in the present NG grid can be safely achieved and/or the amount of investment needed to repurpose it [31]. Additionally, the European Parliament and Council have informally agreed on legislation to promote the uptake of renewable and low-carbon gases, including H_2, in the EU's gas market [32]. This legislation aims to decarbonise the gas sector and secure energy supply and includes measures to facilitate blending H_2 with NG and renewable gases.

Blending H_2 in the existing infrastructure would also allow to import renewable gases from countries characterised by a high renewable potential such as North Africa and Turkey allowing diversification and H_2 production cost reduction [33–35]. Moreover, NG infrastructure could store the daily renewable energy surplus or, by filling underground gas storages, operate as large-scale seasonal storage [36,37].

Focusing on environmental benefits, authors agree that H_2 blending would support the shift toward a more sustainable and low-carbon energy system, and it is an option towards NG sector decarbonization [38]. Davis et al. (2023) estimated a reduction of 1–2% of economy-wide greenhouse gases emissions by using H2NG mixtures for end-users' energy applications [39]. Arpino et al. (2024) [40] estimated to save more than 30 ktons of carbon dioxide (CO_2) per year by injecting H_2 produced by water electrolysis powered by a 500 m^2 photovoltaic plant in Italy. Considering the global Italian energy system and an H_2 concentration of up to 20%vol, Bellocchi et al. (2023) [41] estimated an emission reduction of 15% compared to 2019. Blue H_2 up to 15%vol still allows a reduction of combustion emission of 5% with respect to pure NG and well-to-combustion emissions decrease only in case of 100% carbon capture storage rate [42].

Focusing on social and political aspects, the success of the H_2 market penetration will depend on factors such as H_2 acceptability, policies and regulations, socio-economic factors [43]. A first example of evaluating public perception as a consequence of H_2 blending was published by Scott & Powells (2020) [44]. H2NG blending would play a crucial role in speeding up large-scale projects, facilitating a smoother transition to an H_2-based economy, the diversification of energy sources, and economic opportunities, including job creation, investment in research and development, and the growth of a H_2 related industry. In this respect, GIE supposed that H2NG blending would positively impact the deployment of the H_2 economy in certain countries in the short and medium term. This approach is considered preferable until the construction of new infrastructure exclusively for pure H_2 becomes economically attractive. This conclusion would apply until the cost for the design of a new H_2 pipeline, as modelled, for example, by Brown et al. (2022) [45], is higher than repurposing an existing grid [46,47], allowing to save up to 70–80%vol of the capital expenditure (CAPEX) compared to a new pipeline [48]. GIE also recognized that injecting H2NG mixtures requires preliminary solutions to address policy, regulatory, and technical issues [49]. The National Renewable Energy Laboratory (NREL), part of the U.S. Department of Energy's Office of Energy Efficiency & Renewable Energy, reached a similar conclusion already in 2013. Their report supported the idea that blending H_2 in the short term could increase renewable energy production while ensuring the long-term economic viability of H_2 transportation from production to end-users [50].

Estimating blending potential in existing infrastructure is a well-known problem [28,42,51–57]. However, the real amount of H_2 that can be injected in the grid depends on many factors like the operative conditions, the characteristics of the installed components, and the final use of the gas mixture. For example, Gas Infrastructure Europe (GIE) indicated H_2 compatibility, material selection, leakages including safety outcomes, storage, purity and quality control, gas flow management, monitoring and maintenance, to cost and infrastructure upgrades, and regulatory and policy frameworks among the factors to be faced when defining the upper limit for H_2 concentration (Fig. 1). Extensive research has already given some indications about the potential bottlenecks indicated by GIE.

Focusing on materials H_2 compatibility, San Marchi et al. (2014) [58] review the reference documents to be considered when selecting materials in contact with gaseous high pressure H_2. More recently, Wang et al. (2022) [59] reviewed H_2 blending and pure H_2 projects across the world, reporting positive evidence about the suitability of some of the materials typically used in transmission and distribution pipes

Fig. 1. Diagram of hydrogen injection into natural gas (NG) grid.

(including API5L Grade B/X42/X52 and polyethylene) for H_2 use. Wu et al. (2022) [60] reviewed the H_2-induced failure of high-strength pipeline steels under high pressure. A more specific review focusing on the effect of H2NG mixtures on steel pipelines and potential countermeasure was proposed by Zhu et al. (2024) [61]. The effect of H_2 on valves and welds were published by Jia et al. (2023) [62]. Nitrile Butadiene Rubber (NBR) behavior in presence of H_2 was experimentally investigated by Simmons et al. (2021) finding a potential reduction of the sealing performance due to the increase of the compression set after H_2 exposure [63]. Moreover, proper injection plant has to be designed to ensure the homogeneity of the mixture downstream by Khabbazi et al. (2023) [64].

Leakages and safety aspects were also covered in the literature. For example, Liu et al. (2023) [65] addressed H_2 stratification in the pipeline due to the different densities of the gases in the mixture. Wang et al. (2023) [66] 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 (2023) proposed a review aiming to integrate knowledge about material compatibility and safety aspects when transporting H2NG mixtures [67].

Other issues derive from long-term storage. Zivar et al. (2021) [68] review 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.

From a grid management point of view, by injecting H_2, a higher flow rate or operative pressure should be managed to transport the same amount of energy, affecting the performances of the compression stations and, more specifically, their power consumption to maintain the existing energy transmission capacity [69,70]. Moreover, the end-user's capability to receive H_2 mixed with NG can limit the concentration in the gas mixture.

From the results of the most recent research, however, blending H_2 with NG allows the use of most of the existing NG appliances, such as heaters, boilers, and industrial equipment, without requiring immediate or extensive modifications in case of less than 20%vol H_2 [71,72]. The "Appliance and Equipment Performance with Hydrogen-Enriched Natural Gases" report from the Canadian Standards Association (CSA) Group also presented how H_2 can be blended with NG for use in existing heating systems, boilers, and industrial equipment [73]. The study found that such integration does not require immediate and extensive modifications. The report examines the performance of appliances using H2NG blends of up to 15%vol H_2, focusing on how the appliances ignite, operate, and produce combustion products. The study concludes that these appliances experience no significant operational issues with increased H_2 content. Furthermore, the research "Hydrogen use in natural gas pipeline" [74], authored by UL Solutions, provides an overview of the potential of H_2 blending with NG for use in existing gas-fired appliances. The report presents that existing NG appliances perform well with H_2 blends of approximately 20%, demonstrating the practicality of H_2 blending in current energy systems. Wahl & Kallo (2020) [75] reviewed H_2 blended gas engines confirming the increase of NO_x emissions while significant Total Hydrocarbon Content (THC) reduction is only visible under very lean operation.

Several national initiatives testify the interest to test H2NG blending in existing burners, boilers and heating appliances, in domestic, commercial and industrial sites, as examples: the Project Hy4Heat in UK [76], the Kiwa Project on Ameland, Netherlands [77], the Field Tests in Germany, at Erfstadt near Cologne, up to 20% H_2 content [78] and at Oehringen [79] up to 30% and the tests by the Italian main TSO, SNAM, at Contursi (Italy) up to 10% H_2 in NG [80].

The injection of H_2 into the NG grid encounters key legal and administrative challenges, such as complex existing laws or the lack of clear permitting guidelines, divergent regulations on allowable H_2 concentration levels in NG grids, and contractual and billing issues based on calorific value or Wobbe Index. Additionally, stringent safety standards for the connection and injection of H_2, and diverse types of end-user equipment, complicate the process [81].

The hydrogen working group operated by CEN-CENELEC has identified the need for standardised H_2 admixture into the NG network. A consensus on acceptable H_2 concentration levels within the European NG system is still lacking. The group recommends that relevant standardisations, including gas quality, compressor stations, and metering, should be established within a specific timeframe [82]. These include developing new materials compatible with H_2 [83], creating more accurate and reliable gas sensors [84], establishing clear and consistent regulations for H_2 injection into NG grids [85], and exploring cost-effective strategies to convert existing NG infrastructure for H_2 compatibility [86].

Addressing the technological issues is essential to ensure safe, efficient, and effective H_2 integration into the gas grid's NG flow [87–90]. Simultaneously, a comprehensive review of the current normative and standards framework for NG metrology is essential to identify and address any existing gaps [91]. Cakir et al. (2023) [85] reviewed the regulatory limits related to H_2 blending, highlighting the lack of a clear vision and the need to support studies to define which standards are affected and need to be revised to accommodate higher H_2 amounts.

In addition to the technological challenges highlighted by GIE [13], it is important to highlight the importance of ongoing research and development. Collaboration between academic, industrial, and governmental entities plays a vital role in finding solutions. This includes improving materials to make infrastructure parts stronger and more compatible, using advanced monitoring and control systems to safely integrate H_2 into NG grids, and creating solid rules to guide this change. Over the years, several European and national projects focusing on these aspects have been funded [92–100].

A point of debate relates to the optimal blending composition. In this respect, the research results are quite consistent in indicating that "there is no unique limit for a general blending cap for hydrogen-natural gas mixtures" [101] or "a unique and common technical standard, at the European level, dealing with the maximum acceptable hydrogen fraction into NG networks is still lacking" [30], confirming the view reported in the Standard EN 16726 2015 "at present, it is not possible to establish a limit value for hydrogen that is universal for all areas of

European gas infrastructure, and therefore a case-by-case analysis is recommended" [102].

However, due to the significant acceleration in H_2 deployment and exploitation impressed by the EU H_2 Strategy in 2020, completing the analysis has become urgent.

Regarding gas grid metrology, one of the still debated questions regards the respect of metrological requirements when measuring mixtures containing H_2 in transmission and distribution grids with traditional devices without any repurposing. Since the elaboration of fiscal billing is based on their input, any error greater than the allowed threshold would result in an underestimation or overestimation of gas volumes affecting, respectively, the gas operators or the customers.

The injection of H_2 into NG significantly impacts the physical and thermodynamic properties of the fluid, together with its energy content, due to the blending specific heat and calorific value dependence on H_2 blending percentage 87,103–110. In particular, regarding those properties on which the meters' measurement rely, increasing the H_2 content: decreases the fluid relative density, increases the speed of sound along the blend, increases the viscosity, increases the pressure drops, increases temperature drops, increases the volume flow rate, decreases the higher calorific value significantly (e.g., for gases characterised by a low content of CH_4, the calorific value is reduced by 20% when the H_2 content is equal to 25%) [105]. Consequently, several aspects related to gas metrology need to be checked when dealing with H2NG blending: the classification of gases in EN437; the limits of applicability for each measurement technique to be taken into account in the relative technical standard; the instrumentation endurance and ageing; the instruments' tightness; the algorithms to be used for calculation of compression factor; data correction at specific pressure and temperature conditions; the instrument's calibration; the instrument's accuracy variation [104–110]. The lack of data on all these aspects represents the gaps towards an assessed scientific and technological base over which the metrological technical standard can be reliably elaborated.

To give a definitive answer, the industry sector is seeking experimental evidence. Projects like NewGasMet, Decarb, Met4H2, and other research results have provided the first inputs about the metrological performances of traditional gas meters when H2NG mixtures flow through the pipes [111–113]. However, numerous technologies and models currently installed in European grids are still missing. Therefore, the need for technological advances or the revision of relevant technical standards cannot be confirmed yet.

The EU co-funded THOTH2 Project [114] aims to provide inputs to the technical committees of relevant standardisation bodies to support updating the metrology framework to assess the suitability of existing NG grids in transporting and distributing H_2 ranging from 0%vol to 100%vol in volume.

The paper aims to provide a comprehensive overview of the existing state of the art and to discuss possible inputs for the relevant working groups. Specifically, the focus is on the relevant normative and technical standards currently in force for the measuring devices installed in the European transmission and distribution gas grid investigated in Task 1.3 of the THOTH2 project, entitled "*Actual standards and main Regulation, Codes and Standards*". To achieve the goal, the paper is structured as follows: in the first section, a preliminary overview of the normative metrological framework in European NG transmission and distribution sectors is reported distinguishing between Directive and technical standards. Following, a review of the recent projects about the impact of H2NG and pure H_2 in the relevant standards is proposed. The third section discusses the requirements for increasing integration of H_2 and H2NG blends in the grid from a standardization perspective. Finally, the main conclusions and expected further steps to allow an increasing amount of H_2 in the gas grids are indicated.

2. The European gas metrology normative framework and hydrogen impact: state–OF–the-art

The European normative framework is divided between Directives and technical standards. While the firsts are mandatory, the adoption of the technical standards is on a voluntary basis. Focusing on gas metrology, the European Commission established mandatory regulations for commercialising measuring equipment through the EU Directive 2014/32/EU, also known as the Measuring Equipment Directive (MID) [115]. Furthermore, due to the risk of occurrence of an explosive atmosphere, the gas measuring equipment also has to be compliant with Directive 2014/34/EU (i.e., ATEX Directive) [116]. While no legal obligation applies, manufacturers usually adopt harmonised standards to design and test measuring devices compliant with their requirements. The technical standards are prepared, proposed, and periodically revised within the European Committee for Standardization Technical Committees (CEN TCs), formed by experts from the national standardisation body members [117]. **These standards must enable to demonstrate compliance of measuring instruments with the Essential Requirements of Directive 2014/32/EU.** As a public process, the proposal of work that may lead to the development of the update of a European Standard is open to the community. It ensures a consensus among all parties involved in the drafting process and conformity with the MID essential requirements. Specifically, the European Committee for Standardization/European Committee for Electrotechnical Standardization (CEN/CENELEC) Technical Committees play a crucial role in addressing the European technical standards for NG metrology. While the CEN Sector Forum Gas supports the activities [117], dedicated Technical Committees are responsible for the specific topics, e.g., the CEN/CLC/JTC 6 is in charge of "*Hydrogen in Energy Systems*", the CEN/TC 237 is of "*Gas meters*", the CEN/TC 238 of "*Test gases, test pressures, appliance categories, and gas appliance types*", CEN/TC 234 of "*Gas infrastructure*", including H_2 and H2NG mixture injection and metrological aspects.

Recognising H2NG as a useable gaseous fuel, its transportation and distribution through the existing gas grid evidences several gaps in the related normative framework. This is because H_2 admixing into the existing gas grids alters various physical and thermodynamic properties of the fluid [104–106]. Consequently, every standard governing gas grid metrology requires revision, starting with those concerning gas classification and testing. The meters currently installed for fiscal purposes on the transmission and distribution grids across Europe vary in type, including diaphragm, ultrasonic, turbine, rotary, and Coriolis meters. Each type is regulated by a specific standard to ensure the accurate determination of gas volume, mass flow, volumetric flow, gas quality, and the related energy content [117]. All these types of gas measuring equipment must be evaluated for their capability and measurement accuracy when used with H2NG blends. Additionally, they need to be verified for calibration, tightness, endurance, and ageing issues. At the same time, the algorithms used for calculating certain gas properties under varying pressure and temperature conditions, such as the compression factor, must be adapted to include the effects of blending. The results of the experimental campaigns provide a scientific database upon which the Technical Standard governing gas grid metrology can be updated to accommodate H2NG blending as a fuel. The gaps in the regulation can be recognized in the lack of sufficient data on the behaviour of gas meters when H2NG flows through them. The set of normative standards was selected to include all standards governing gas grid metrology in accordance with the European Clean Hydrogen Alliance [100] and Marcogaz [117].

Fig. 2 provides a visual representation of the European regulatory framework for gas metrology. In the following sections, the main conclusions on how H2NG mixtures can impact the existing European metrology normative framework will be described.

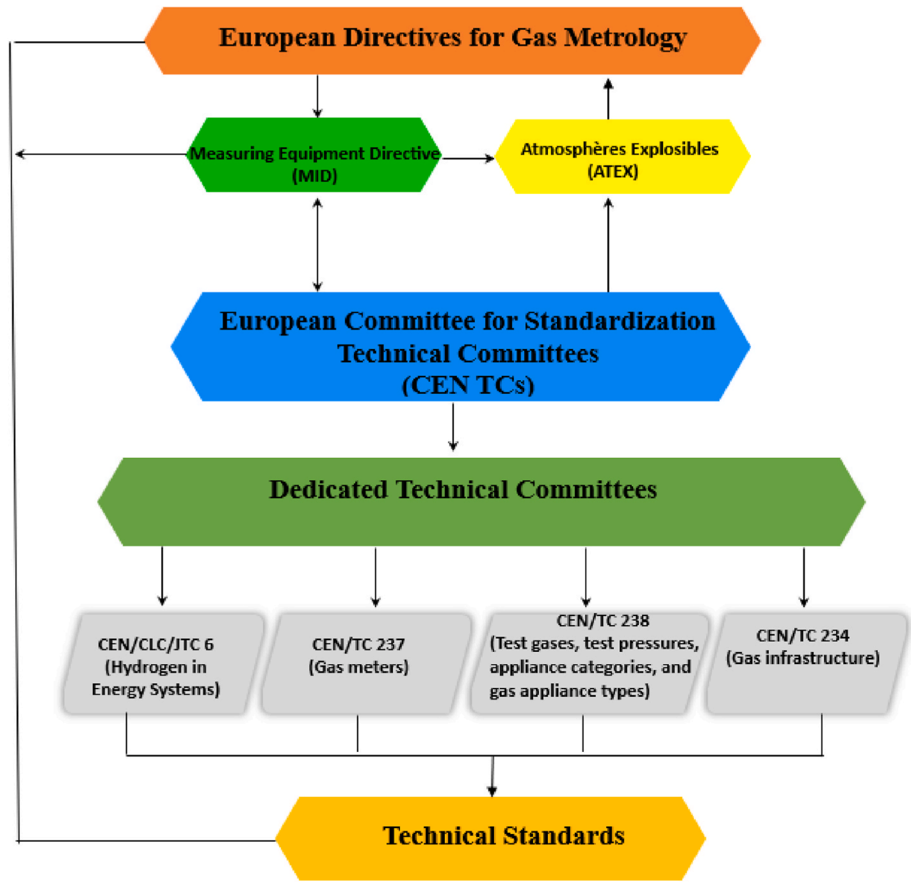

Fig. 2. European regulatory framework for gas metrology.

2.1. *The Directive 2014/32/EU (measuring instruments Directive - MID)*

The Measuring Instruments Directive (MID) sets the essential requirements for measuring instruments to circulate freely within the EU, including the large variety of utility meters such as gas, electric, water, thermal meters, and volume-conversion devices.

In accordance with the provisions of the MID, Annex IV (MI-002), a gas meter is a device designed to measure, store and display the amount of gas (volume or mass) that has flowed through it. Therefore, the definition does not limit a gas based on its composition. The MID does not limit the use of gaseous fuels only to gases of families 1, 2 and 3 according to the EN 437 standard 118,119.

Specifically, MID indicates the minimum thresholds for the acceptability of a gas meter by defining the Maximum Permissible Error (MPE), the minimum rangeability or turndown. The MPE is also defined for the volume gas converters to be commercialised in Europe.

There is no necessity to modify the MID itself in view of introducing H2NG blends into the NG grid, as it defines general rules of acceptability that are not affected by metering technical aspects and that will not be changed by H_2 blending.

2.2. *Technical standards*

Many technical standards apply to NG transmission and distribution in the metrology sector. While some of these standards are harmonised with the MID [115], other ones have been promoted by different institutions. Since the analysis of the single sentence in each code is out of the scope of this paper, the following sections aim to propose an overview of the impact of H_2 and H2NG mixture injection for the relevant standards organized by similar themes.

2.2.1. *Gas classification, tests conditions, and measuring system requirements*

There are four technical standards that primarily cover the topic of gas classification, operative test conditions, and measuring systems within the European technical standard framework. These standards, e.g., EN 437, EN ISO 13443, EN ISO 13686, and EN 1776, are summarised in Table 1. Furthermore, the "Status" column indicates if the standard is currently under review, revision, preparation, or identification process to account for H_2 injection into the gas grid [100].

The EN 437, published on July 31, 2021 by CEN/TC 238, specifies the test gases, test pressures, and appliance categories relative to gaseous fuels [118]. Gases are categorised into three families and sub-groups based on the gross Wobbe Index (*IW*), which is expressed in MJ/m^3. The *IW* is a parameter used to assess the interchangeability between gases and is defined as the ratio of the gas calorific value per unit volume to the square root of its relative density under the same conditions. The so-called "City gas", containing H_2 and other gases like, for example, carbon monoxide and dioxide, belongs to the 1^{st} family, whereas H_2 and CH_4 belong to the 2^{nd} family, as shown in Table 2. The boundary within which the *IW* must lie for common rich NG burners is between 48 and 58 MJ/m^3. As Mostefaoui (2020) reported [123], only a few manufactured gases contain more than 50% vol limiting the maximum amount of H_2% to be tested with standardised mixtures. For example, the so-called "G112" mixture has the highest percentage of H_2 (59%vol), while CH_4 and nitrogen (N_2) are respectively 17%vol and 24 %vol respectively. NG sector stakeholders agree to an H_2 threshold value of up to 20–30%vol [101,124], i.e., a value included in the current range of values. To date, transporting pure H_2 in new dedicated grids has been considered the preferred option for greater concentrations because most sectors planned to retrofit their appliances to 100%vol H_2 [125]. Moreover, Marcogaz (the European gas TSOs and DSOs association)

Table 1
European Standards for Gas Classification, Testing, and Conditions (including Standards in preparation, under revision or in the identification process).

Normative	Title	Technical Committee	Working Group	Last revision	Status
EN 437 [118]	Test gases - Test pressures - Appliance categories	CEN/TC 238	WG1	2021	Under revision by CEN TC 238
EN ISO 13443 [120]	Natural gas - Standard reference conditions			1997	To be identified by CEN TC 238 and ISO TC 193
EN ISO 13686 [121]	Natural gas - Quality designation			2013	–
EN 1776 [122]	Gas infrastructure- Gas measuring systems - Functional requirements	CEN/TC234	WG 5	2016	In preparation

Table 2
Wobbe Index and family for the most common combustible gases [118].

GAS	WOBBE INDEX (*IW*) MIN. & MAX.		FAMILY
Hydrogen	40.65	48.23	2H
Methane	47.91	53.28	2H
Ethane	62.47	68.19	3
Ethylene	60.02	63.82	3
Natural Gas	48.52	53.71	2H
Propane	74.55	81.07	3
Propylene	71.88	77.04	3
Butane	85.09	92.32	3
Isobutane	84.71	91.96	3
LPG	79.94	86.84	3
Acetylene	59.17	61.32	2H
Carbon Monoxide	12.80	12.80	1

recently estimated that the revamping cost of existing grids for pure H_2 transportation would be less than 20% of CAPEX for new-build infrastructure [126]. However, the possibility of testing pure H_2 conditions has not yet been considered.

EN ISO 13443 defines the standard reference conditions of temperature, pressure and humidity to be used for measurements and calculations carried out on NG and similar fluids, as prepared by ISO/TC 193 "Natural Gas" and confirmed in 2020 [120]. The standard reference conditions are essential for ensuring consistency and comparability of measurements and data related to NG. However, not being included, H_2 blending is not supported by the standard.

EN ISO 13686 specifies the parameters required to describe NG quality. Specifically, calorific value, density, compression factor (Z), and *IW* have to be specified when NG is used as a heating source. However, no threshold exists [121].

EN 1776, which was released in 2016, specifies the functional requirements for the design, construction, testing, commissioning/decommissioning, operation, maintenance, and, when applicable, calibration for all new gas measuring systems [122].

As shown in Table 1, only EN 437 is under revision by CEN/TC 238 [1–4]. Although updated versions were adopted by the plenary CEN/TC 238 in 2019 and 2020, in parallel with CEN/TC 109 [123], several gaps still exist, particularly in gas/hydrogen analysis methods and gas/hydrogen quality monitoring. Several suggestions on how to adapt EN 437 to H2NG blending in the current gas grids have also been proposed by the WP4 of the THyGA (Testing Hydrogen admixture for Gas Applications) Project [127]. The authors consider that "*if distributed gases are going to contain significant hydrogen concentrations, it seems indispensable to differentiate based on the applied burner technology*" [128]. Regarding EN ISO 13443, the adaptations of gas analysis methods and the standard reference conditions when dealing with H2NG blend are still to be defined by CEN/TC 238 [100].

No review activity is expected for EN ISO 13686 since the gas properties to be determined when the gas is used for energetic purposes remain the same even in the case of H_2 or H2NG blend injection in the grid. However, despite H_2 already being included in the list of potential components, an update of the nominal ranges of NG components in European grids could be appropriate, given that the H_2 concentration is currently indicated as less than 0.1% (w/w).

No official activity has been initiated for EN 1776. However, the European Clean Hydrogen Alliance indicated that standardisation activity is being prepared by CEN/TC 234 to comply with the transport and distribution of H2NG mixtures into the gas grids. However, since EN 1776 defines functional requirements and good practice during service, no specific section seems to currently hinder the H2NG and pure H_2 operation.

2.2.2. Gas meters technologies

Various measuring principles can be applied to measure NG flow rate, resulting in several different gas meter technologies: rotary, turbine, ultrasonic, diaphragm, thermal mass, and Coriolis. These are the most commonly implemented in the NG transmission and distribution sector. For use in fiscal purposes, the accuracy class and the MPE defined by the MID must be respected. Technical standards play a crucial role by providing guidance to manufacturers for designing, constructing, and testing gas meters under specific operative conditions. These conditions are typically defined in terms of gas families, working pressure, flow rate, and temperature ranges. Table 3 summarises the development and evaluation status of the European standards for the gas meter devices on the NG grids, the TC/WG by which it was published and the last revision date. The "Status" column indicates whether the standard is under preparation and identification to account for H_2 injection into the gas grid [100].

Sector stakeholders have started to investigate the potential impacts on the existing technical standards when H_2 or H2NG are blended, as schematically shown in Table 4.

2.2.3. Gas properties measurements

Table 5 summarises the current EU standards for gas properties measurements, along with the TC/WG and the last revision date. The "Status" column indicates whether the standard is currently under preparation and identification to account for H_2 injection into the gas grid [100].

When dealing with gas properties, it is essential to ensure accurate calculations to avoid billing errors. Since the ideal gas law can be applied in these cases, the compression factor must be calculated. The ISO 12213 series is used for this purpose [142–144].

ISO 12213 specifies methods for calculating the compression factors of NG and similar mixtures under conditions where the mixture can exist only as a gas. This standard consists of three parts: the ISO 12213-1 [142], titled "Introduction and Guidelines", prepared by Technical Committee ISO/TC 193; the ISO 12213-2 [143], titled "Natural gas – Calculation of compression factor – Part 2: Calculation using molar-composition analysis" reviewed and confirmed by ISO/TC/SC1 193 specifies a method for the calculation of compression factors when the detailed composition of the gas by mole fractions is known, together with the relevant pressures and temperatures, while the ISO 12213-3 [144], titled "Natural gas – Calculation of compression factor – Part 3: Calculation using physical properties", reviewed and confirmed by ISO/TC 193/SC 1 in 2021, specifies a method for the calculation of compression factors when the superior calorific value, relative density and CO_2 content are known, together with the relevant pressures and

Table 3
European standards under preparation and identification for gas meter devices.

Normative	Title	Technical Committee	Working Group	Last revision	Status
EN 12480 [129]	Gas meters - Rotary displacement gas meters	CEN/TC 237	WG2	2018	In preparation By CEN/TC 237 ISO/TC30
EN 12261 [130]	Gas meters - Turbine gas meters		WG3	2018	In preparation By CEN/TC 237 ISO/TC30
EN 14236 [131]	Gas meters – Ultrasonic domestic gas meters		WG9	2018	In preparation By CEN/TC 237 ISO/TC30
EN 1359 [132]	Gas meters - Diaphragm meters		WG8	2017	In preparation By CEN/TC 237 ISO/TC30
EN 17526 [133]	Gas meters – Thermal mass flow meter-based gas meters		WG10	2022	In preparation By CEN/TC 237 ISO/TC30
ISO 10790 [134]	Measurement of fluid flow in closed conduits-Guidance to the selection, installation and use of Coriolis meters (mass flow, density and volume flow measurements)	ISO/TC30	SC5	2015	To be identified
ISO 17089 [135]	Measurement of fluid flow in closed conduits_ Ultrasonic meters for gas		SC5	2019	In preparation By CEN/TC 237 ISO/TC30

Table 4
Potential impacts of H_2 or H2NG blending on gas meters technical standards.

Type	Elements to be considered with H2/H2NG blending
Rotary	To be checked: Materials compliance with H_2 and H2NG mixtures; Tightness tests; Measurement accuracy and its dependence on H_2 content, especially at a low flow rate
Turbine	Measurement uncertainties can be affected due to the lower density with respect to NG. Preliminary results show that the effect of H_2 in high-pressure applications is negligible with respect to the calibration error limits [136]. CEN/TC 237–N764 validated the use of turbine meters for a mixture of up to 10%vol H_2 [85].
Ultrasonic	No influence on the deterioration of metrological properties was found for domestic ultrasonic gas meters tested with the use of various gas mixtures with H_2 content up to 10%vol. Specifically, experimental tests demonstrated that ultrasonic gas meters are not significantly affected by H_2 injection up to about 10 %vol [105]. The speed of sound increases up to 12.3%vol, becoming generally higher than the accepted limit of 475 m/s indicated by EN 14236 at an H_2 content of 5%vol. One gas that exceeds the limits of ultrasonic meters is the test gas G 222 that has a speed of sound of 497 m/s due to the **23% H_2 content"**
Diaphragm	To be checked: Materials compliance with H_2 and H2NG mixtures; Endurance tests, Tightness tests; Measurement accuracy, starting flow rate and its dependence on H_2 content. The long-term effect also needs confirmation. Different meter design and materials can be implemented [137]. Preliminary results seem to show no significant effect on metrological performance with varying H_2 content from 0%vol to 15%vol [104] and 50%vol [93].
Thermal mass	EN 17526 was the first gas meter standard updated in order to include renewable gases such as H_2 and biomethane. For gas mixtures containing from 0% to 5% vol H_2 content, a significant majority of the results met the requirements of the MPE [138].
Coriolis	The use of H_2 significantly modifies the accuracy [93–95], requiring specific calibration of the Coriolis flow meter using H_2 gas in substitution of water [139–141]. The European Clean Hydrogen Alliance indicates that ISO 10790 needs to be modified by CEN/TC 237 and ISO TC 31 to comply with using H2NG blending in the gas grids, but no standardisation project has been identified to date [100].

temperatures.

When the gas composition is known, calorific values, density, relative density, and Wobbe indices are calculated using EN ISO 6976 [145], published in 2016 by ISO/TC 193. Additionally, ISO 15970, converted into EN 15970 in 2014 by CEN/TC 238 [146], provides guidelines for the general measurements of gas properties. Specifically, this standard gives requirements and procedures for measuring NG properties that are used mainly for volume calculation and conversion, i.e., density at reference and operating conditions, pressure, temperature, and compression factor.

The measurement of gas composition is covered by EN ISO 6974 (parts 1-2-3-6) [147–150] and EN ISO 6975 [151]. Both standards refer to gas chromatographic methods to determine gas composition. Specifically, ISO 6974 describes methods of NG analysis and methods for calculating component mole fractions and uncertainties. ISO 6974 is intended for measuring H_2, He, O_2, N_2, CO_2, and hydrocarbons, either as individual components or as a group, when the mole fraction ranges from 0.0001%vol to 40%vol. The EN ISO 6975 [151] describes the specifications for the quantitative analysis of NG components, limiting the ranges from 0.001%vol to 0.5%vol.

Regarding gas meters, the sector stakeholders have already started to check the potential impacts of H_2 injection on relevant standards. Other results available in the literature are shown in Table 6.

2.2.4. Gas properties conversion

Table 7 summarises the EU standards under preparation and currently in use for the conversion of gas properties, the TC/WG by which it was published, and the last revision date. The "Status" column indicates whether the standard is under preparation or in use to account for H_2 injection into the gas grid [100].

Gas volume conversion is regulated by EN 12405-1 [158], published in 2018 by CEN/TC 237, and revised in 2021. The standard specifies the requirements and tests for the construction, performance, safety and conformity of gas-volume electronic conversion devices associated with gas meters used to measure volumes of fuel gases. Specifically, three types of conversion devices within the scope of the standard are usually installed and operated in gas grids, i.e., i) conversion as a function of temperature only (the so-called "T conversion"); ii) conversion as a function of pressure and temperature with a constant compression factor ("PT conversion"); iii) conversion as a function of pressure, temperature, taking into account also the gas compression factor ("PTZ conversion"). EN 12405-2 [159] regulates the conversion devices for energy conversion installed in the gas grid. Finally, EN 12405-3 [160] regulates flow computers.

By analysing these standards, the following H_2 and H2NG blending impacts have been identified in the literature. Concerning EN 12405-1 and EN 12405-3, the main obstacle in applying the conversion method to H2NG mixtures containing H_2 content ranging from 20%vol up to 100%vol would lie in investigating the most suitable equation of state for accurately determining the density. While "P" and "PT" conversion devices correct the conversion factor only based on actual pressure and

Table 5
European standards under development and identification for NG properties measurements.

Normative	Title	Technical Committee	Working Group	Last revision	Status
EN ISO 12213-1 [142]	Natural gas - Calculation of compression factor - Part 1: Introduction and guidelines	CEN/TC 238	WG1	2006	In preparation by CEN/TC 238
EN ISO 12213-2 [143]	Natural gas - Calculation of compression factor - Part 2: Calculation using molar-composition analysis			2009	In preparation by CEN/TC 238
EN ISO 12213-3 [144]	Natural gas - Calculation of compression factor - Part 3: Calculation using physical properties			2010	In preparation by CEN/TC 238
EN ISO 6974-1 [145]	Natural gas – Determination of composition by gas chromatography_ General guidelines and calculation of composition	CEN/TC 238 ISO/TC 193 SC1	WG1	2018	To be identified by CEN TC 238
EN ISO 6974-2 [146]	Natural gas - Determination of composition by gas chromatography - uncertainty calculations			2012	To be identified by CEN TC 238
EN ISO 6974-3 [147]	Natural gas - Determination of composition by gas chromatography – Precision and bias			2018	Under review
EN ISO 6974-6 [148]	Natural gas – Determination of hydrogen, helium, oxygen, nitrogen, carbon dioxide and C1 to C8 hydrocarbons			2019	To be identified by CEN TC 238
EN ISO 6975 [149]	Natural gas – Extended analysis – Gas-chromatographic method	CEN/TC 238 ISO/TC 193		2022	
EN ISO 6976 [150]	Natural gas – Calculation of calorific values, density, relative density and Wobbe indices from composition	ISO/TC 193 SC1 CEN/TC 238		2016 confirmed in 2022	
EN ISO 20765-1 [151]	Natural gas – Calculation of thermodynamic properties – Part 1: Gas phase properties)	CEN/TC238		Reviewed and confirmed in 2021	
EN ISO 15970 [152]	Natural gas – Measurement of properties – Volumetric properties: density, pressure, temperature and compression factor		WG1	2014	

temperature, respectively, "PTZ" and flow computers require information about the gas mixture concentrations to calculate the compression factor, i.e., the gas density. It is crucial to ensure the availability of relevant process gas chromatograph data for volume conversion and accurate meter measurements [144]. Therefore, the European Clean Hydrogen indicates that a project is in preparation by CEN/TC 2347 and ISO TC30 for EN 12405-1, complying with the use of H2NG blends in the gas grid [100]. EN 12405-2 is also affected by H_2 blending, varying the calorific value depending on the percentage in the blending. In fact, H_2 and NG have different higher heating values (HHV), with HHV(H_2) = 13 MJ/Nm^3 and HHV (NG) = 40 MJ/Nm^3. Therefore, new methodologies to calculate the gas heating value through the network would allow more accurate measurement.

3. Results from other research activities

Normative and standard framework reviews must rely on rigorous scientific results. Generally speaking, there is still a need for more knowledge and scientific evidence on measuring devices' metrological performances when used with H_2 and H2NG blending. Several European projects have been launched to collect missing data and fill in the gaps in the normative framework. These main findings of the completed projects are reported.

The NATURALHY project (2004–2009) [93], participated by a European consortium of 40 partners with extensive experience and skills, aimed to assess the current situation of standards and regulations regarding H_2 and H2NG mixtures. The NewGasMet project was launched in June 2019 to cover gaps related to the potential impact of new gases, particularly H_2, on metrological performance and durability. To determine whether the meters remain compliant with the MID requirements, the most used gas meter technologies in European gas grids were investigated [97]. The results indicated a need for a review of the standards for every type of measuring instrument on the gas grid. Additionally, it was suggested that the conversion procedures and determination of gas physical properties should be performed. Specifically, the expert group of the project made some recommendations on several standards covered by CEN/TC 237. The gas meters' metrological performance should be validated with the gas closest to its intended use, not air. Concerning gas turbine meters, the Reynolds number range (±5%) should be considered in the assessment. Finally, tests could be carried out at zero flow conditions to minimise the required gas volume and associated safety concerns and provide a worst-case scenario test with the poorest signal-to-noise ratio.

The HIGGS (Hydrogen In Gas GridS) Project was launched to identify the technical and regulatory barriers to using the existing NG grid for transporting H2NG mixtures or pure H_2 [137]. Focusing on the European high-pressure gas transmission infrastructure, the project results give clear indications. Regarding materials, the literature review indicates potential limitations in the use of some steel grades (i.e., X65 and X80) with H2NG or pure H_2. At the same time, the gaskets currently installed in the networks and made of different elastomers could be affected by an increase in diffusion and permeability. Regarding metrology, supported by the results of a survey of European gas TSOs, the project confirmed the capability of ultrasonic meters to operate up to a 20%vol content, while content up to 100%vol for diaphragm and rotary-bellow types was indicated. Regarding standardisation, the project confirmed the difficulties in adapting existing standards due, first of all, to the lack of a clear vision about which H_2 concentrations the provisions in the European standards need to cover even if most of the technical committees put as a target the 20%vol.

GERG, under the umbrella of CEN/TC 234, was appointed in 2019 to carry out the Project titled "*Removing the technical barriers to the use of hydrogen in natural gas networks and for gas end users*". The project's objectives were to increase knowledge about the impact of renewable gases on the accuracy and durability of commercially available meters and to provide reliable data for adapting gas meter standards, if necessary [161]. Barriers hindering the possibility of H2NG mixtures flowing in the current grid were identified. Recommendations are given for lowering or removing these barriers, i.e., to perform laboratory and field tests to investigate the effect of H_2 on the meter's accuracy and endurance and to develop H2NG blending-adapted calibration methods.

The EU-funded THyGA Project (Testing Hydrogen Admixture for Gas Appliances) [127] aimed to investigate the impact of H2NG blends on end-use applications, specifically in the domestic and commercial sectors. The project clarified the effect of H_2 injection on NG quality properties. The project results pointed out that up to 20% vol H_2 content, the gas mixture can be classified in the 2nd gas family while regarding the Wobbe index limits, H2NG with H_2 content up to 6%vol can be considered in the H group, up to 60%vol in the E group, according to EN 437 [162]. However, it is suggested to use a 20%vol. H_2 in CH_4 blend as a reference gas to test appliances due to safety considerations [163].

A comprehensive overview of available test results and regulatory limits for H_2 admission into existing NG infrastructure and end-use was published by Marcogaz in 2019 [155]. No significant issues are

Table 6
Potential impacts of H_2 or H2NG blending in gas properties measurement standards.

Normative	Elements to be considered with H2/H2NG blending
EN ISO 12213-1 EN ISO 12213-2 EN ISO 12213-3	The H_2 content in the mixture has to be known to apply the method reported in the standard. Some aspects to be checked and eventually revised have been identified: The SGERG-88 equation by Jaeschke et al. (1991) [152] for the calculation of compression factors and gas law deviation factors was reported in 1997). A limit of 10% mol is defined for H_2 content in EN ISO 12213-3. Furthermore, the relative density is limited to the range between [0.55,0.80]; corresponding to a density at standard conditions of [0.711,1.034] kg/m^3: for some compositions of NG. This results in a maximum H_2 content of 5%mol. To enable the calculation of compression factors at a higher H_2 content, the existing algorithm has been modified by the German Technical and Scientific Association for Gas and Water [153]. Dell'Isola et al. (2021) [105] analysed the effect of H2NG mixtures on the main thermophysical parameters as a function of H_2 concentration up to 25% vol. The study shows the trend of the compressibility factor *Z* as a function of H_2 injection using the available calculation algorithms of ISO 12213-2, ISO 12213-3, AGA NX 19 and AGA NX 19 Mod. The results show that H_2 influences the compressibility factor *Z* at high pressures more than at low pressures. Moreover, the impact of H_2 with pressure on the compressibility factor *Z* is more significant at low H_2 contents. A similar behaviour has been found for the volume conversion factor.
EN ISO 6974-1 EN ISO 6974-2 EN ISO 6974-6 EN ISO 6975	When H_2 is a gas component, i.e., not present in the trace as a contaminant, the measuring analysis methods must be adapted. The composition analysis standards need to be deeply upgraded for new chromatograph techniques. The EN ISO 6974 needs to be modified by CEN TC 238, but the topics are still to be identified [100]. Van der Veen et al. (2015) [154] checked if ISO 6974 can be validated for use with H2NG blends, finding that the scope of the current ISO 6974 can be extended to cover NG compositions with H_2 amount-of-substance fractions of up to 20%vol. It has to be noted that process gas chromatographs installed in the existing NG infrastructure are usually designed for H_2 concentrations smaller than 0.2%vol potentially requiring intervention by retrofitting an additional separating column of argon as a carrier gas for H_2 detection or by using new process gas chromatographs [101,155,156].
EN ISO 6976	The methods of calculation require values for various physical properties of the pure components. Experimental checks of the suitability of the EN ISO 6976 to accept the H2NG blend as an "NG substitute" have to be performed. The gross calorific value for gas in the presence of H_2 must be measured by certified analysers, and the relative standards must be prepared and published. European Transmission System Operators (TSO) are involved in an analysers' replacement program on their networks, to accurately measure the H_2 content in CH_4/H_2 mixtures [157].
EN ISO 15970	This standard needs to be continuously verified and updated, in particular in the case of flowing of gases of different physical and thermodynamic properties, such as H2NG blends.

evidenced in the referenced literature for all the most used gas meters, up to 10%vol H_2 in NG. Conflicting experimental results were found at higher H_2 concentration blends in the 10–40%vol range for turbine and rotary displacement gas meters and the 10–100%vol range for diaphragm gas meters. Most available studies show positive results of up to 40%vol H_2 concentration for volume converters. The widely accepted limit for H_2 concentration in NG is 10%vol, which allows the use of all the existing gas metering system types and conversion algorithms without any need for change [164,165]. This assumption is based on the slight change in physical parameters of the gas blend concerning NG, as supported by experimental results. Higher compatibility levels are not excluded, as they may be possible depending on the measurement method but require further investigations [166].

4. Discussion: gaps toward H_2 and H2NG grids metering

To prepare for the introduction of H_2 into the existing gas transmission and distribution infrastructure, there is an urgent need for normative bodies and their Technical Committees (TCs) to undertake essential updates. While the identification of TCs is underway, most of the Regulations, Codes, and Standards (RCS) updates are in progress for each meter type, except Coriolis meters.

In this direction, the Hydrogen Task Force is finalizing a SoA report based on technical tests conducted with H2NG mixtures across different elements of the gas value chain. This report aims to identify future research actions. Specifically, the CEN/TC 234 WG5 and WG11 have contributed to sections related to the transport metering chain and the gas quality within the report, respectively.

CEN/TC 237 collaborated with Marcogaz and Farecogaz (i.e., the European Association of the Manufacturers dealing with the gas metering chain, gas pressure regulators with associated safety devices, and relevant stations) to produce a joint report that provides a qualitative assessment of the impact of H_2 on meters. Additionally, CEN/TC 237 is in the process of revising EN 1359 and EN 12480 to introduce H2NG mixtures [167]. A comprehensive review of the European normative framework regulating the metrology of devices installed along the transmission and distribution gas grid, specifically in the case of H_2 injection at content percentages up to 100%vol, has been undertaken. This review is referenced in the European Clean Hydrogen Alliance's "*Roadmap on Hydrogen Standardization*", published in March 2023 [100].

Based on the analysis of each standard, along with findings from similar projects and related papers, a comprehensive list of gaps can be outlined that is applicable across various meter types.

- Lack of test results on physical and thermodynamic properties of H2NG mixtures at different operative conditions, i.e., temperature, pressure, and H_2 content.
- Lack of long-time and endurance tests on metering device materials.
- Lack of data on metrological and mechanical performances for flow rate greater than the nominal one.
- Lack of exhaustive data on the accuracy of each meter at different H2NG blends.
- Lack of information on gas meters' tightness at different H_2 content in H2NG mixtures.

Table 7
European standards in preparation and currently in use for converting gas properties.

Normative	Title	Technical Committee	Working Group	Last revision	Status
EN 12405-1 [158]	Gas meters - Conversion devices - Part 1: Volume conversion	CEN/TC 237	WG4	2021	In preparation by CEN/TC 237 ISO/TC30
EN 12405-2 [159]	Gas meters - Conversion devices - Part 2: Energy conversion			2021	
EN 12405-3 [160]	Gas meters - Conversion devices - Part 3: Flow computer			2015	
EN ISO 14912	Gas analysis - Conversion of gas mixture composition data	CEN/TC 238	WG1	2006 Confirmed in 2021	

- Lack of information on meters calibration linearity at different H_2 content in H2NG mixtures.
- Lack of suitable modelling tools to predict the physical and thermodynamic properties of H2NG blends from tested experimental conditions and extend the applicability range.
- More experimental data to simulate the expected operative conditions are needed.

Advanced monitoring and control systems are crucial in effectively managing the increasing H_2 content within gas networks. These systems are instrumental in providing real-time insights, enhancing safety, optimising network performance, and facilitating proactive decision-making. This is essential to ensure the reliable and efficient operation of gas networks that incorporate H_2.

One of the key aspects of H2NG grids is gas composition measurement through gas chromatography. While there is recognition of the need to address this issue and update relevant standards, no concrete actions have been taken thus far.

However, it is important to note that determining the appropriate H_2 content in the H2NG mixture, which warrants standard revision, requires consensus among all stakeholders involved. To avoid setting unrealistic targets, a preliminary assessment suggests that a reasonable target of up to 30%vol should be considered for gas-measuring devices. This is contingent on these devices being capable of maintaining sufficient accuracy without experiencing long-term degradation. Therefore, the standardisation roadmap should be defined within this limit to facilitate the successful integration of H_2 injection into NG grids.

5. Conclusions

This review article highlights the crucial need for a complete check and revision of the European normative framework regulating the metrology of devices installed along the gas transmission and distribution infrastructures, in the case of H2NG blending from 0 to 100%vol H_2.

H2NG blends differ from the actual NG flowing in the gas grids in several aspects; those that affect the measurement of gas volumetric flow along the pipelines, based on the actual metrology equipment, are gas density, viscosity, compression factor, specific heat capacity, speed of sound along the fluid, volume flow rate, temperature and pressure drops, Wobbe Index and the dependence of the thermophysical parameters on the operating condition, i.e. pressure and temperature. Moreover, gas composition and quality determination assume a critical role. Issues related to gas meters accuracy, testing procedure, material compatibility against H_2 ageing, tightness and calibration with H2NG mixtures at different compositions need to be assessed by a pre-normative experimental activity and shared among the experts of the dedicated Technical Committees to individuate the recommendations and limits for the state-of-the-art meter technologies such as the need to develop new solutions to overcome these thresholds. Safety concerns require rigid leak detection procedures to be established. All these items will support the revision of the actual standards on gas grid metrology.

The revision work is currently in progress within several CEN TCs in charge of updating the standards, particularly CEN/TC 237 and CEN/TC 238, which are responsible for standards related to gas metering devices and the determination of gas quality parameters.

These CEN TCs collaborate closely with the International Standardization Organization (ISO), receiving support from experts representing national committees, TSOs, Distribution System Operators (DSOs), industrial entities, governmental bodies, and associations. The regulatory process needs to rely on widespread, solid, and shared experimental activities focusing on metrological performances of the installed meters, materials compatibility, conversion algorithms, and endurance tests to identify the gaps for H2NG mixture measurements.

Several gaps regarding meter tightness, calibration, gas composition, and safety have already been pointed out, but the explored percentage range of H_2 volumes in the H2NG mixture still needs to be improved. Several standards, particularly those related to the different gas meters, will be updated in the next years. A step behind this is updating the rules on gas composition by gas chromatography since it is still to be addressed. Furthermore, standardisation works are required regarding leak detection since no comprehensive legal framework is currently available. Experimental data are still needed to investigate the compatibility of the existing standards with H2NG mixtures and pure H_2. However, due to the complexity of the standardisation process, the research activities should be participated by all the interested stakeholders, including the members of the relevant TC, gas TSOs and DSOs, measuring devices' manufacturers, National Metrological Institutes and research institutes.

A comprehensive and harmonised approach to address the significant requirements for updating the European normative framework could be implemented by a collaborative effort within the International, European and National normative bodies (e.g., ISO, CEN, CENELEC, etc.) with support from experts and organisations across various sectors unlocking the full potential of H2NG blending as a clean and sustainable energy solution.

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.

Acknowledgment

This work was funded by European Commission through the Clean Hydrogen Partnership under Grant Agreement No 101101540. This Partnership receives support from the European Union's Horizon Europe Research and Innovation program, Hydrogen Europe and Hydrogen Europe Research.

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