Recent progresses in H₂NG blends use downstream Power-to-Gas policies application: An overview over the last decade

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HIGHLIGHTS

- Review of studies on hydrogen-enriched natural gas blends.
- Power-to-Gas concept and motivation for hydrogen injection into the gas grid.
- Effects of hydrogen in gas pipelines and hydrogen embrittlement issues.
- Analysis of effects on end use devices and discussion of safety issues.
- Economics aspects and price of hydrogen-methane blends.

ARTICLE INFO

ABSTRACT

This paper attempts to give a broad overview on technologies progress status, effects, perspectives, and issues associated to H₂NG widespread applications. It deepens and completes the content of previous reviews by including hitherto unreviewed aspects as far as possible. To do so, a holistic approach has been used by surveying technical, energy, environmental, economic and safety issues related to the hydrogen mixtures' use. This review aims to provide support for a broader understanding of the problem, starting from the simple list of mixtures properties up to their impact on both NG pipelines and end-use devices. Hydrogen injection affects several blend characteristics and gas network parameters. Mixing limits are also related to Wobbe index variations and safety aspects due to the flashback risk. Numerous works have shown that hydrogen fractions of 10% allow parameters to be kept within acceptable ranges, and up to 20% are not related to significant risks.

Introduction

Growing awareness of human-induced climate change is accelerating the energy transition process. As IPPC's findings have shown, the risk of exceeding the 1.5 °C level of global warming can lead to irreversible damage to ecosystems and humans [1]. Already today, climate change has resulted in more frequent and intense extreme events, causing

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widespread negative impacts, damaging natural and human systems, and worsening economic and social conditions [2]. The transformation of energy systems is a priority and significant global efforts will be needed to decarbonise the world economy.

Hydrogen can play an important role in decarbonising energy systems [3]. Renewable energy sources (RES) share is rapidly increasing and 100% renewable power systems are expected in the coming decades [4]. Nevertheless, to integrate such high shares of non-programmable generation, long-term energy storages are crucial [5].

Power-to-Gas (PtG) systems represent an option to address that issue by converting electricity into hydrogen by means of the electrolysis process [6]. PtG application as a sector coupling strategy for storing the excess of renewable energy sources (RES) has been widely discussed in recent years [7,8].

Hydrogen end-uses in future renewable energy systems will be numerous [9]. Current hydrogen demand in the industry is mainly supplied by the steam methane reforming process. That demand can be replaced by green hydrogen hailing from water electrolysis. Furthermore, green hydrogen can be applied in high-temperature industrial processes as well as in the chemical industry mainly for producing ammonia and methanol.

In addition, hydrogen can be used in the mobility sector either directly or through conversion into fuel alternatives [10]. There are very few fuel cell vehicles in operation in the world due to their current lack of economic competitiveness with both conventional and electric vehicles [11]. Furthermore, for the development of hydrogen mobility, the widespread deployment of hydrogen refuelling stations will be necessary [12]. The synthesis of electro-fuels allows the use of hydrogen in existing means of transport and is especially interesting for decarbonising heavy transport [13].

The role of hydrogen has been also investigated to balance fluctuating renewable generation on the power grid [14]. Nevertheless, as assessed in Ref. [15], hydrogen does not represent the best solution for balancing variable generation due to the low round-trip efficiency of the Power-to-Gas-to-Power process.

The main barrier to the development of a hydrogen economy is the lack of transport and distribution infrastructure [16]. Moreover, the construction of the necessary new infrastructure will require over several billion dollars in the coming decades [17].

The hydrogen injection into the natural gas (NG) grid can represent a viable option for using hydrogen during the energy transition towards decarbonised energy systems [18]. Indeed, NG pipelines can accommodate low volumetric fraction of hydrogen without significant changes in the operating parameters of the network and end-user devices [19]. Such a solution exploits the gas grid as a low-cost form of hydrogen storage and transport and can drive the early-stage development of the hydrogen economy without the need for dedicated infrastructure [20]. Furthermore, interest in the direct replacement of NG with alternative fuels has grown strongly recently, especially in Europe due to the current energy markets crisis for geopolitical reasons.

In NG-based countries, such as UK, Italy and USA, more than 50% of households are connected to gas networks [21].

Despite the electrification of the heat demand is considered as the main strategies for decarbonising the building sector, the rapid replacement of all the heating plants is unrealistic, since it requires large retrofitting of homes. Therefore, in those countries, the Hydrogen enriched Natural Gas (H_2NG) blends can support the emissions reduction of the building sector during the energy transition phase [22].

Hydrogen injection leads to a change in several mixture parameters and they can affect NG networks [23]. In detail, the major concern related to hydrogen blending is hydrogen embrittlement in iron and steel pipes, which can lead to crack propagation in pipelines [24]. In addition, changes in the combustion properties of natural gas can also affect the performance of NG end-use devices [25]. Blending limits are due to variations in thermal input caused by variations in the Wobbe Index and safety aspects related to variations in flashback risk [26]. Nevertheless, several works demonstrated that the hydrogen blending up to 15–20% by volume should be allowable [27]. Furthermore, 20% by volume seems to be a viable hydrogen share for both domestic burners and NG end-user devices [28].

Literature survey and scope of the review

The literature on hydrogen blends is extensive, as well as the one regarding the hydrogen effects on the gas pipeline. In the last decade, a few studies reviewing the subject have been published.

Schiebahn et al. [29] provided a technological overview by investigating different PtG pathways in the context of a case study in Germany. They analysed the state of the art on both water electrolysis and methanation processes and gave a brief overview of the hydrogen impact on pipelines and end-use equipment. Messaoudani et al. [30] provided a summary of the main hazards and risks associated with hydrogen blending into a natural gas network. Furthermore, they reviewed the most recent advances in safety measures, assessed the knowledge gaps and identified potential topics for future research. Their results show that the abundant theoretical work is not yet supported by sufficient experimental work for its validation and further research needs to be done on preventive measures to reduce the risk level. Mehra et al. [31] reviewed studies analysing hydrogen enriched compressed natural gas internal (HCNG) combustion engines. Their study provided a detailed discussion of hydrogen generation methods, the fundamentals of HCNG mixture characteristics and potential fuel refinements. Furthermore, they included an overview on HCNG vehicle's demonstration projects worldwide. Maroufmashat and Fowler [32] analysed several PtG pathways assessing their impact on the Ontario energy system and comparing the overall efficiencies. The assessment of the different system configurations is supported by a brief overview of the main technologies, infrastructures and storage systems. The application of hydrogen blends in the transport sector has been also assessed by Alrazen et al. [33]. They reviewed in detail HCNG applications in reciprocating spark-ignited piston engines, by analysing engine performance, combustion and emission characteristics. Ohaeri et al. [34] published an

important review on hydrogen related degradation in pipeline steel. They assessed the pipeline corrosion due to hydrogen mixing in the gas network, with a precise analysis of the factors influencing hydrogen embrittlement. Furthermore, their work analysed experimental techniques for detecting hydrogen and evaluating degradation in steel and evaluated future perspectives of research on the topic. Quarton et al. [27] provided a review on PtG strategy for injection into the gas grid, by analysing real-life projects, economic assessments and systems modelling studies. That represents the first review in literature analysing the value chain as a whole. However, it focuses mainly on the analysis and comparison of both real projects and techno-economic modelling studies of PtG systems, only mentioning the problems related to H_2NG blends use in pipelines and NG devices. Yan et al. [35] provided a summary of the recent research progress on HCNG applications in spark ignition internal combustion engines. In that work, power, efficiency, combustion and emission characteristics of hydrogen addition, were analysed. Furthermore, other hydrogen-enriched fuels for internal combustion engines were also briefly discussed. The study developed by Gondal et al. [36] provided an overview of several PtG projects concentrated mainly in Europe analysing impacts of hydrogen injection into the NG pipelines. Furthermore, that work assessed how the gas quality is affected by the hydrogen blending. The approach applied was to analyse each element of the NG infrastructure by evaluating its degree of acceptability of hydrogen concentration. Laureys et al. [24] recently provided a review of factors affecting hydrogen induced degradation. They analysed the structural characteristics of pipelines when hydrogen is blended and assessed how mechanical, material, and environmental variables affect the severity of hydrogen embrittlement. Also Wu et al. [37] reviewed the latest research on the hydrogen-induced failure of high-strength pipeline steels. In detail, they assessed progresses in both experimental and theoretical simulations for the hydrogen embrittlement in steels. In Table 1, a summary of the literature survey has been provided.

Reviews developed in recent years often focus on a single part of the value-chain. In some works [29,32], the general overview is functional for the analysis of potential configurations that can be applied to a case study. Other works [30,34,38,39] focus mainly on the hydrogen impact in the NG pipelines, with a particular attention to the potential risks associated with hydrogen embrittlement. Several studies [31,33,35] focus on the application of compressed mixtures in internal combustion engines in the transport sector.

Only a few papers analyse the value-chain as a whole, providing a significant contribution to the literature on the subject. Nevertheless, they focus heavily on the analysis of real projects and the mathematical modelling of PtG systems.

Much of the literature analyses the topic of hydrogen blends with a narrow scope. In contrast, this review proposes a holistic approach to the problem by analysing the various issues and involved aspects.

The purpose of this study is to present a broad review of effects, perspectives and issues of H_2NG applications, taking in consideration the whole value-chain. A holistic approach has been proposed in the discussion, analysing technical, energy, environmental, economic and safety issues related to the use of

hydrogen mixtures. This paper aims to provide support for a broader understanding of the problem, starting from the technical reasons for the application of PtG strategies with hydrogen injection into the gas grid up to the impact of such applications on both NG pipelines and end-use devices. In addition, the structure of the paper partially follows the value-chain of such a solution, starting from production to the different end-uses.

In Section Literature survey and scope of the review, the PtG concept has been presented, by discussing reasons for hydrogen blending and the current political framework. In Section Power-to-Gas Concept, thermophysical properties of H_2NG blends have been discussed. Section H2NG combustion and environmental properties summarises the hydrogen blending effects on NG pipelines, presenting the key issue of hydrogen embrittlement. Section Hydrogen blending effects on NG networks analyses hydrogen effects on gas storage systems. In Section H2NG storage, different H_2NG mixtures end-uses have been analysed. In section H2NG mixtures end-uses, the main safety issues of H_2NG applications are highlighted. Section Economic aspects analyses environmental and economic aspects of the implementation of PtG strategies with hydrogen injection into the NG network. Finally, Section Conclusions summarises the main outcomes and provides concluding remarks.

Power-to-gas concept

The dispatching of intermittent RES generation is the main challenge in the transformation of energy systems. Indeed, a high share of renewable generation requires that system flexibility has to be developed on the demand side and within the system itself [38]. According to Ref. [10], only a 30% share of non-programmable RES can be accommodated by existing power networks. Different demand-response technologies based on short-term energy storage, such as vehicle-to-grid or power-to-heat strategies, can substantially increase the renewable penetration. However, moving towards the complete decarbonisation of the power system will require the extensive implementation of long-term energy storages and PtG systems will play a key role in the integration of excess renewable generation [39].

The PtG strategy consists of converting renewable electricity into hydrogen by means of the electrolytic process.

Several papers in recent years have reviewed the state of the art of electrolytic technologies [40,41]. Alkaline electrolysers represent the technology standard and are the most commercially available option [42]. PEM (proton exchange membrane) electrolysers are characterised by higher power density, hydrogen purity and pressure operating conditions [43]. However, these advantages are currently offset by higher costs [44]. SOECs (solid oxide electrolysis cell) are based on the water splitting reaction at high temperature (600 °C–900 °C), which significantly increases electrical efficiency [45]. Such technology is not yet at a commercial stage and installation costs are much higher than for low-temperature electrolysers [46].

In Fig. 1, a schematic view of PtG system with hydrogen blending into the gas grid is shown.

Hydrogen is an interesting option for renewable energy storage, but its application presents numerous problems. Despite a very high energy density (120–142 MJ/kg), hydrogen

Table 1 – Summary of the literature survey.

Authors	Title	Scope of the article	Topic	Year	Ref.
Schiebahn et al.	Power to gas: Technological overview, systems analysis and economic assessment for a case study in Germany	Investigation of different PtG pathways in the context of a case study in Germany	The whole value-chain	2015	[29]
Messaoudani et al.	Hazards, safety and knowledge gaps on hydrogen transmission via natural gas grid: A critical review	Review of the main hazards and risks associated with hydrogen blending into natural gas networks	NG pipelines	2016	[30]
Mehra et al.	Progress in hydrogen enriched compressed natural gas (HCNG) internal combustion engines - A comprehensive review	Review of HCNG applications in internal combustion engines	Transport sector (HCNG)	2017	[31]
Maroufmashat and Fowler	Transition of future energy system infrastructure; through power-to-gas pathways	Assessing different PtG pathways assessing their impact on the Ontario energy system	The whole value-chain	2017	[32]
Alrazen et al.	HCNG fuelled spark-ignition (SI) engine with its effects on performance and emissions	Review of HCNG applications in reciprocating spark-ignited piston engines	Transport sector (HCNG)	2018	[33]
Ohaeri et al.	Hydrogen related degradation in pipeline steel: A review	Assessment of pipeline corrosion due to hydrogen mixing in the gas network	NG pipelines	2018	[34]
Quarton et al.	Power-to-gas for injection into the gas grid: What can we learn from real-life projects, economic assessments and systems modelling?	Review of PtG strategy for injection into the gas grid, by analysing both real-life projects and techno-economic modelling studies	The whole value-chain	2018	[27]
Yan et al.	Application of hydrogen enriched natural gas in spark ignition IC engines: from fundamental fuel properties to engine performances and emissions	Summary of the recent research progress on HCNG applications in spark ignition internal combustion engines	Transport sector (HCNG)	2018	[35]
Gondal et al.	Hydrogen integration in power-to-gas networks	Overview of several PtG projects concentrated mainly in Europe analysing the degree of acceptability of hydrogen concentration for each element of the NG infrastructure	The whole value-chain	2019	[36]
Laureys et al.	Use of existing steel pipeline infrastructure for gaseous hydrogen storage and transport: A review of factors affecting hydrogen induced degradation	Assessment of the impact of mechanical, material and environmental variables on the severity of hydrogen embrittlement	NG pipelines	2022	[24]
Wu et al.	From the perspective of new technology of blending hydrogen into natural gas pipelines transmission: Mechanism, experimental study, and suggestions for further work of hydrogen embrittlement in high-strength pipeline steels	Review of progresses in both experimental and theoretical simulations for the hydrogen embrittlement in steels	NG pipelines	2022	[37]

is the lightest of the known elements and this results in a low volumetric energy content (13 MJ/m3) [47]. Because of that, compression and liquefaction processes result in energy losses of around 10% and 40%, respectively [17]. Many safety issues are also related to the very high flammability of hydrogen, which is an important barrier especially in residential applications [48]. In addition, huge investments are needed in the near future to develop a suitable infrastructure for hydrogen transport and storage, and such a network will take several years to build.

Existing NG grid can represent a cost-effective means for storing and transporting hydrogen. Hydrogen can directly replace NG by contributing to the partial decarbonisation of the gas network [49]. In such a way, emissions related to gas consumption in different energy sectors can be reduced without changing the existing infrastructure or end-use devices [50].

The rapid reduction of NG consumption is a topical issue, especially in Europe and all importing countries. In the recent period, gas prices in Europe have risen sharply, creating a negative impact on the economy in the delicate recovery phase of the post-pandemic era. The deployment of H_2NG blends can support the reduction of gas consumption especially in those countries like Italy, Germany or the UK, which base a large part of their national energy consumption on NG.
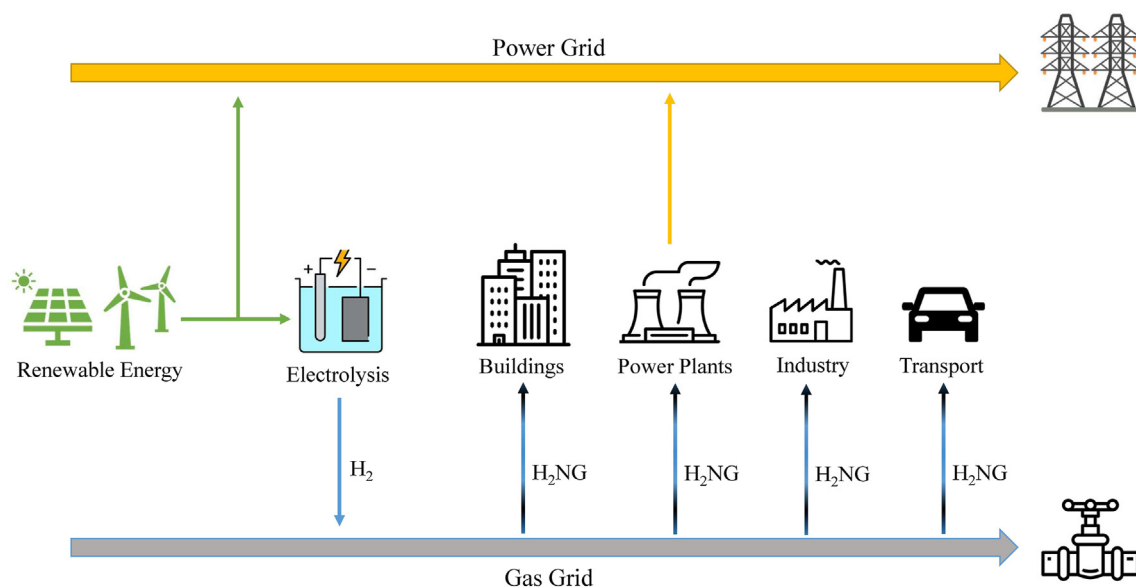
Fig. 1 — Schematic view of PtG system with hydrogen blending into the gas grid.

Political and legislative framework

Political interest in the development of a hydrogen economy has grown in recent years. Several countries have recently adopted national energy strategies, setting targets on hydrogen production and electrolysers' installation. On July 8, 2020, the European Commission presented 'A hydrogen strategy for a climate-neutral Europe', which sets ambitious targets on hydrogen production [51]. The plan calls for the installation of 40 GW of electrolysers and the production of 10 million tonnes of renewable hydrogen by 2030.

Several member states have already developed their own strategies and defined their own targets. Most strategies have set as their main objective the capacity of electrolysers to be installed in a given period. That is useful at an early stage to accelerate the deployment of hydrogen production, in order to stimulate the learning process and reduce the electrolyser installation cost and, consequently, the Levelized Cost of Hydrogen [52]. Indeed, the rapid reduction of the hydrogen production cost represents the main driver for the development of the entire hydrogen value-chain.

Several national strategies envisage the blending of hydrogen into the gas grid and some countries already allow it and have ad-hoc legislation [53].

France and Spain have a hydrogen blending limit of 6% and 5% by volume, respectively. Other European countries set limits of 4% or less. Only Germany goes further, allowing up to 10% of hydrogen, but only under certain conditions and infrastructure sections.

The existing blending limits are very restrictive compared to those successfully tested in the literature. Other countries, such as Italy, do not currently have legislation dedicated to hydrogen blending, but their strategy encourages such a solution in the next decade [54].

As also emphasised in Ref. [21], legislation on the subject is still to be developed in most countries and much of the existing regulation is outdated and needs to be updated in the near future. In Table 2, limits for hydrogen blending into the gas grid in existing national regulations have been summarised.

H$_2$NG combustion and environmental properties

Combustion properties of hydrogen enriched natural gas blends are strongly affected by the hydrogen addition. The most notable properties to mention, which can be useful for energy and environmental purposes, are brought in Table 3 with varying the volumetric hydrogen fraction ($f_{H2,vol}$) [56].

As suggested by Table 3, hydrogen eventually increases the mixtures gravimetric Lower Heating Value however it goes in contrary over the volumetric one. This is due to the significant gap between density of natural gas and hydrogen implying that growing $f_{H2,vol}$ in the mixture lessen all of volumetric thermophysical properties. Substantially, to provide the same energy amount burning 1 Nm^3 of NG a higher mixture flow rate is required.

Table 2 — Limits for hydrogen blending into the gas grid in existing national regulations [55].	
Country	Blending limit (maximum)
Germany	10%
France	6%
Spain	5%
Austria	4%
Switzerland	2%
Finland	1%
Netherlands	0.5%
UK	0.1%
Belgium	0.1%
Japan	0.1%

Table 3 – List of H₂NG combustion properties with varying the volumetric hydrogen fraction.

$f_{H2,vol}$ (% vol.)	ρ_n (kg/Nm³)	LHV (MJ/kg)	LHV' (MJ/Nm³)	α_{st} (kg$_{air}$/kg$_{fuel}$)	α'_{st} (Nm³$_{air}$/Nm³$_{fuel}$)	[CO₂]$_{th}$ (% vol.)	[CO]$_{th}$ (% vol.)
0	0.717	49.98	35.857	17.391	9.569	11.669	14.977
5	0.686	50.46	34.6196	17.506	9.210	11.535	14.757
10	0.655	50.99	33.3822	17.656	8.851	11.390	14.519
15	0.623	51.57	32.1448	17.766	8.492	11.231	14.263
20	0.592	52.22	30.9074	17.918	7.234	11.058	13.986
25	0.561	52.93	29.67	18.087	6.900	10.869	13.684
30	0.529	53.73	28.4326	18.275	6.566	10.661	13.355

The same behaviour can be registered referring to the stoichiometric air to fuel ratio (α_{st}), which is defined as the air mass needed to fully oxidize 1 kg of fuel (see Equation (1)).

$$\alpha_{st=} \left(\frac{\dot{m}_{air}}{\dot{m}_{fuel}} \right)_{st} \qquad (1)$$

Indeed, it tends to increase as more hydrogen is added, while it shrinks once it is evaluated in volumetric terms. In combustion application that issue is crucial since, referring to the chemical reaction, the oxygen stoichiometric coefficient decreases. Therefore, burning H₂NG blends within the same device requires less oxygen, hence less air, than pure NG, and when the air flow rate is constant the combustion process automatically occurs in leaner conditions. For that reason, adjustment systems for keeping under control the air to fuel ratio to constant values must be envisaged and developed.

Table 3 also provides the undiluted values of carbon dioxide and monoxide, which are functional parameters for measuring the emissions by using commercial exhaust gas analysers based on the Ostwald combustion equation. The so called theoretical or undiluted volumetric concentration, i.e. [CO₂]$_{th}$ and [CO]$_{th}$, can be derived from the theoretical equation for complete and incomplete combustion as introduced in Ref. [57].

$$[CO_2]_{th} = \frac{\frac{C}{12}}{\frac{C}{12} + \frac{1-m}{m}\left(\frac{C}{12} + \frac{H}{4}\right)} = \frac{m}{1 + (1-m)3\frac{H}{C}} \qquad (2)$$

In Equation (2), which is based on the stoichiometric complete combustion equation of carbon and hydrogen chemical reaction separately, C, H and m can be defined assuming simplified air composition (i.e. Nitrogen and Oxygen volumetric concentrations are 79.1% and 20.9%, respectively).

Hence: $m = 0.209$; $C = 22.414c$; $H = 22.414h$ where c and h represent carbon and hydrogen mass fractions within the fuel (kg/kg$_{fuel}$) and 22.414 mol/Nm³ denotes molar volume under normal conditions (T = 273.16 K, pressure 1.013 bar).

In the case of incomplete combustion, instead of carbon dioxide, carbon monoxide is produced. Referring to stoichiometric combustion and following the same approach [CO]$_{th}$ can be evaluated as follows:

$$[CO]_{th} = \frac{\frac{C}{12}}{\frac{C}{12} + \frac{1-m}{m}\left(\frac{C}{24} + \frac{H}{4}\right)} = \frac{m}{1 + (1-m)\left(3\frac{H}{C} - \frac{1}{2}\right)} \qquad (3)$$

It is important to highlight that the Ostwald procedure is currently used to easily measure on field the energy performance of both traditional and condensing boilers for civil and industrial applications.

As aforementioned, by adding hydrogen the fuel volumetric LHV tends to decrease. Therefore, it is very important to understand how much energy can be transferred and delivered through an orifice or a pipeline when different gaseous blends are available within the same infrastructure. A useful indicator to measure the interchangeability of gaseous fuel is presented as Wobbe Index, which compares energy output of different gases during combustion process. Basically, the gases showing the same value of Wobbe index, despite their own chemical composition, are able to deliver the same amount of energy through a nozzle (at the choking condition and the same pressure) [58]. It can be formulated as:

$$W = \frac{H_{vol}}{\sqrt{d}} \ (MJ / Nm^3) \qquad (4)$$

where H_{vol} is the volumetric Lower Heating Value (MJ/Nm³), d denotes the gaseous fuel relative density in accordance with Equation (5).

$$d = \frac{\rho_{gas}}{\rho_{air}} \qquad (5)$$

And finally, ρ_{gas}, ρ_{air} are the densities under normal conditions (kg/Nm³).

In Table 4 the volumetric LHV, the relative density and the Wobbe index values associated to eight different natural gas compositions have been outlined.

Thereafter, by using the reference gaseous fuels reported in Table 4 the Wobbe index variations, with changes in the hydrogen fraction, have been calculated and depicted in Fig. 2.

From data analysis, it emerges how, generally for all of the selected gas compositions, the Wobbe index tends to almost linearly decrease as the hydrogen fraction increases. Moreover, it is worth of noticing that the trend lines reach their minimum values when the hydrogen content in the blends ranges in 70% vol. – 90% vol. A similar conclusion can be found in literature [56], where the authors analysed the Wobbe index referred to the Higher Heating Values.

Anyway, in the present analysis, it has been registered that, for all those gas compositions characterised by a certain content of an inert, such as the nitrogen, those minimum values occur in the span 70% vol. – 80% vol. Conversely, when inert gases are lacking, the minimum points shift towards the right-hand side. Besides, some intersections between the different curves can be identified. In this case, since two different gaseous fuels show the same Wobbe index value, it entails that they are interchangeable from a transport of energy point of view.

Table 4 – Volumetric LHV, relative density and the Wobbe index values of different Natural Gas compositions.

NG Typology	Chemical Composition [% vol.]				LHV [MJ/Nm^3]	Normal density [kg/Nm^3]	Relative density to the air	Wobbe Index [MJ/Nm^3]
	CH_4	C_3H_8	H_2	N_2				
G 20	100	0	0	0	35.900	0.714	0.553	48.298
G 21	87	13	0	0	43.414	0.876	0.678	52.717
G 23	92.5	0	0	7.5	33.208	0.754	0.584	43.469
G 24	68	12	20	0	37.798	0.739	0.572	49.983
G 25.3	88	0	0	12	31.592	0.778	0.602	40.709
G 27	82	0	0	18	29.438	0.810	0.627	37.174
G 27.4 A	78	0	0	22	28.002	0.831	0.644	34.903
G 222	77	0	23	0	30.106	0.570	0.441	45.318
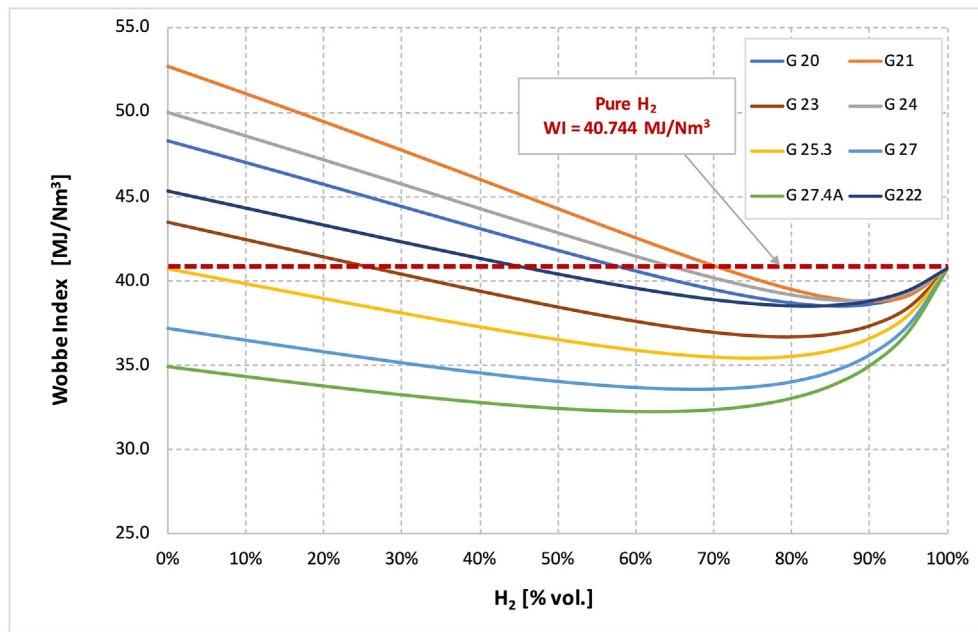
Fig. 2 – Wobbe Index as a function of H_2 fraction in the mixture.

One of the main characteristics of a fuel combustion is known as burning velocity. It is an intrinsic fuel property that directly affects the burning combustion rate in the internal combustion engines, and it is related to flashback, which can damage burners or cause flame extinction. Hydrogen enrichment effectively increases the burning velocity [26].

The effect of hydrogen addition on flame velocity was studied experimentally in literature [25,59–61]. As reported in Ref. [62], hydrogen injection exponentially increases the flame speed. Such result is illustrated in Fig. 3.

Laminar burning velocity is defined as the velocity at which unburned gases move through the combustion wave normal to the surface. The laminar burning velocity (S_μ) can be derived as follows [25]:

$$S_\mu = S_n \frac{\rho_b}{\rho_u} \tag{6}$$

In Equation (6), ρ_b and ρ_u are the burned and unburned gas densities, respectively, and S_n is the stretched flame velocity:

$$S_n = \frac{dr_u}{dt} \tag{7}$$

where r_u is radius of flame photograph and t is the elapsing time from ignition. The stretch rate α is defined as:

$$\alpha = \frac{1}{A} \frac{dA}{dt} \tag{8}$$

here, A is the area of the flame; for spherically outward expanding flame front, α can be derived as:

$$a = \frac{1}{A} \frac{dA}{dt} = \frac{2}{r_u} S_n \tag{9}$$

Finally, with respect to early flame expansion, a linear correlation between flame speed and stretched flame velocity reads as:

$$S_\mu - S_n = L_b \alpha \tag{10}$$

In Equation (10), L_b is Markstein length which characterizes the variation in local flame speed due to the influence of external stretching, and it determines the flame stability with respect to preferential diffusion [63].

In [64] the influence of H_2 fraction and equivalence ratio has been measured for blending ratios equal to 0% vol., 5%
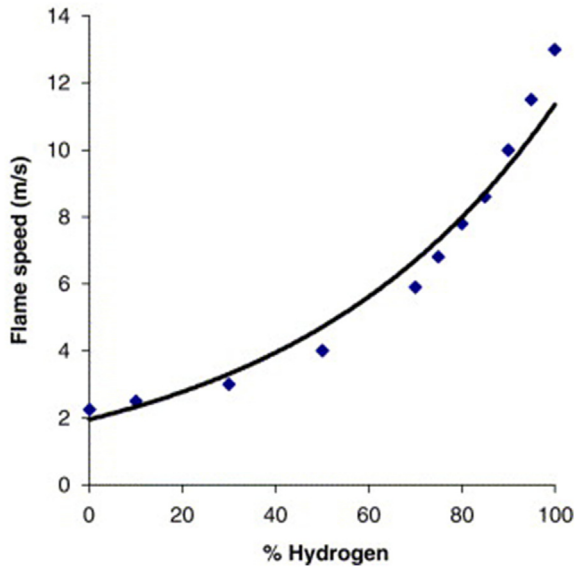
Fig. 3 – Hydrogen fraction effect on flame speed for $\lambda = 1$ (stoichiometric combustion). Source: Ref. [62].

vol., 10% vol., 25% vol. and 50% vol. and they are shown in Fig. 4. The Equivalence ratio is defined as follow:

$$\Phi = \frac{1}{\lambda} \qquad (11)$$

As regards the environmental implications related to the blends burning, it is necessary to remark some technical issues to properly evaluate the contribution to the decarbonisation process. Once a reference flow rate of gaseous fuel is considered, the carbon dioxide emissions equally diminish as the hydrogen fraction in the blend increases. Basically, over the mixing process there is a physical carbon atoms substitution with the hydrogen ones, resulting in less carbon dioxide pollution. Nevertheless, hydrogen is characterised by a very low density compared to the other gaseous fuels, so that when it is blended, the mixture Wobbe Index as well as the

volumetric LHV tend to decrease in accordance with Fig. 2. It entails that, to deliver the same released energy by a pure gas, a higher flow rate is required. As a consequence, the beneficial effect is strongly reduced since the carbon free property of hydrogen is not able to completely offset the energy density penalisation. For those reasons, it is better to use as an indicator the carbon dioxide emissions per unit of energy instead of per unit of mixture volume. Referring to the sample gases reported in Table 4, the specific carbon dioxide emissions per unit of energy with changes in the hydrogen fraction have been calculated. All of the results have been plotted in eight different charts, as depicted in Figs. 5 and 6.

From data it emerges how the carbon dioxide emission tends to slightly decrease almost linearly up to a hydrogen fraction equal to 30% vol. for each gas. Moreover, the trend lines slope depends on the original natural gas composition. Specifically, the larger the inert gas fraction, the larger the slope is, such as for the G 27, G 27.4A G 25.3, G 222. types.

Finally, the relative carbon dioxide reduction can be rapidly evaluated by using the chart reported in Fig. 7. Referring to the area of interest for typical end users' devices (i.e. hydrogen content ranging in 0% vol. − 40% vol.) and assuming, for instance, an enrichment equal to 30% vol., the CO_2 emissions can be reduced from 9.56% up to 14.08% less. In detail, those values can be accomplished when the G 21 and G 27 types are used as a reference natural gas for blending, respectively. In the case of pure methane, namely the G 20 type, the achievable percentage reduction is limited to 11.33%. Notwithstanding, out of the area of interest the maximum span associated to the G21 and G 27 use can be registered at 70% vol. of hydrogen content. Beyond that threshold value the gap in the environmental performance between the two gases progressively tends to zero.

In the end, it is possible to state that the G 21 gas type is the most suitable for blending purpose, since it shows the highest environmental performance; furthermore, even if the carbon reduction associated to the blending, in absolute terms, implies a modest environmental contribution to the decarbonisation pathway (compared to other strategies), it still remains
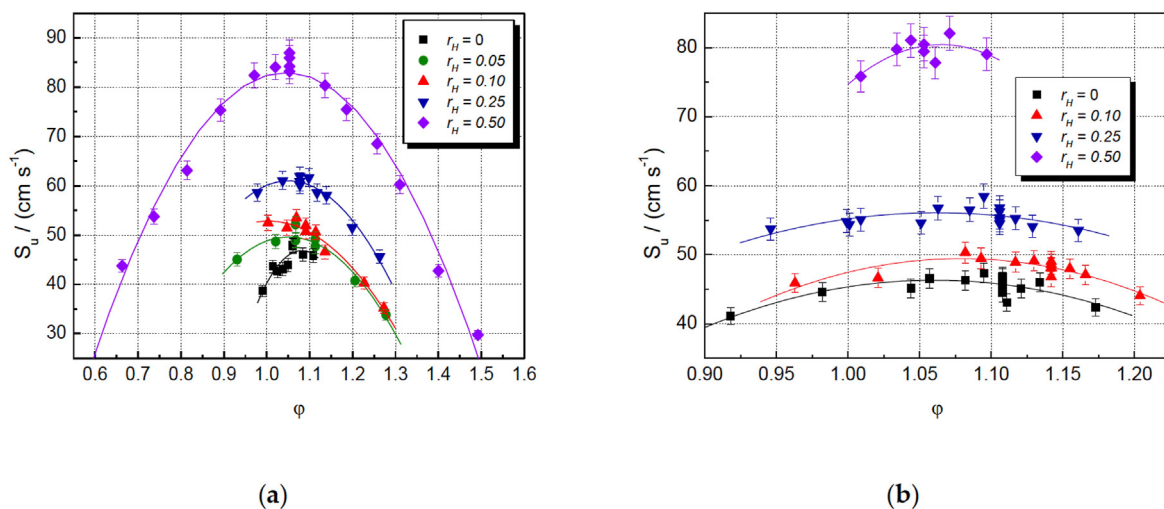

(a)

(b)

Fig. 4 – Experimental laminar burning velocities of single fuel−air and multifuel−air mixtures vs. the equivalence ratio with various r_H at ambient initial H2−air; (b) NG−H2−air mixtures. Source: Ref. [64].
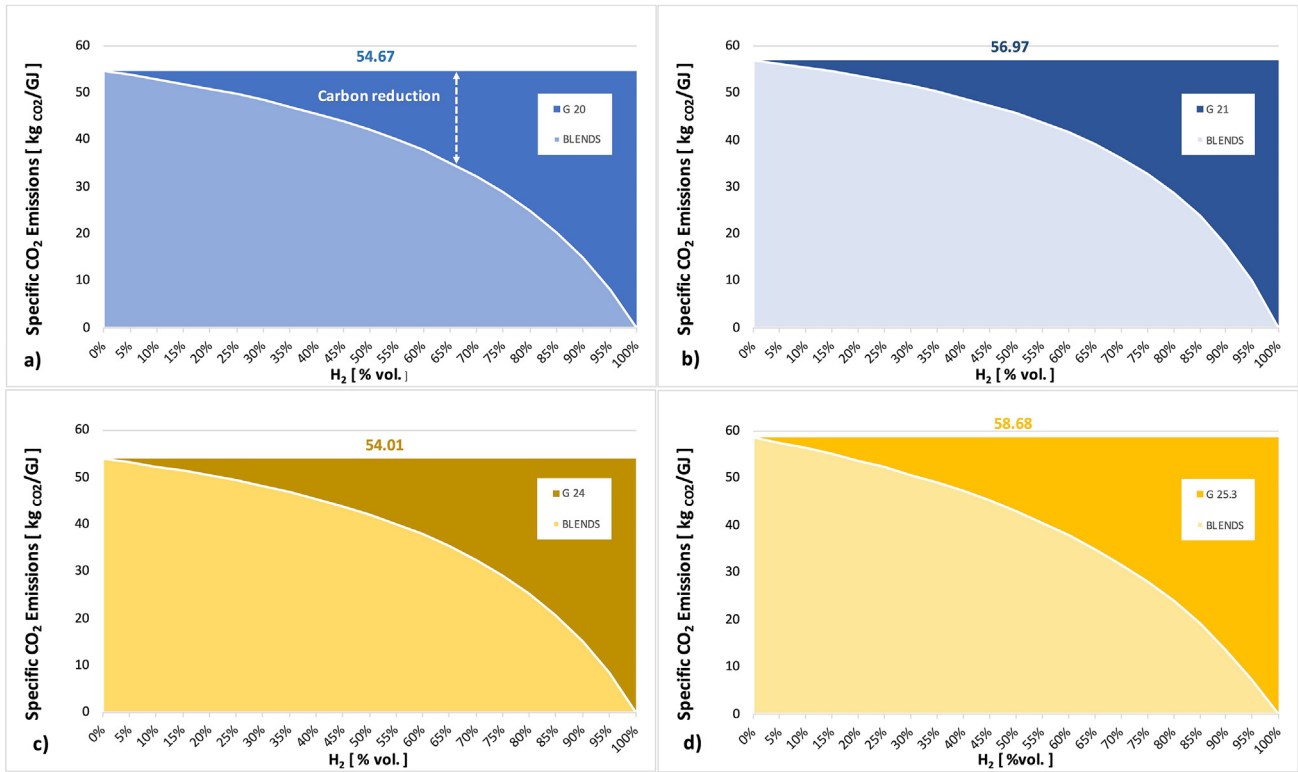
Fig. 5 – CO_2 specific emissions vs. hydrogen fraction for different Natural Gas types: a) G 20; b) G 21; c) G 24; d) G 25.3.
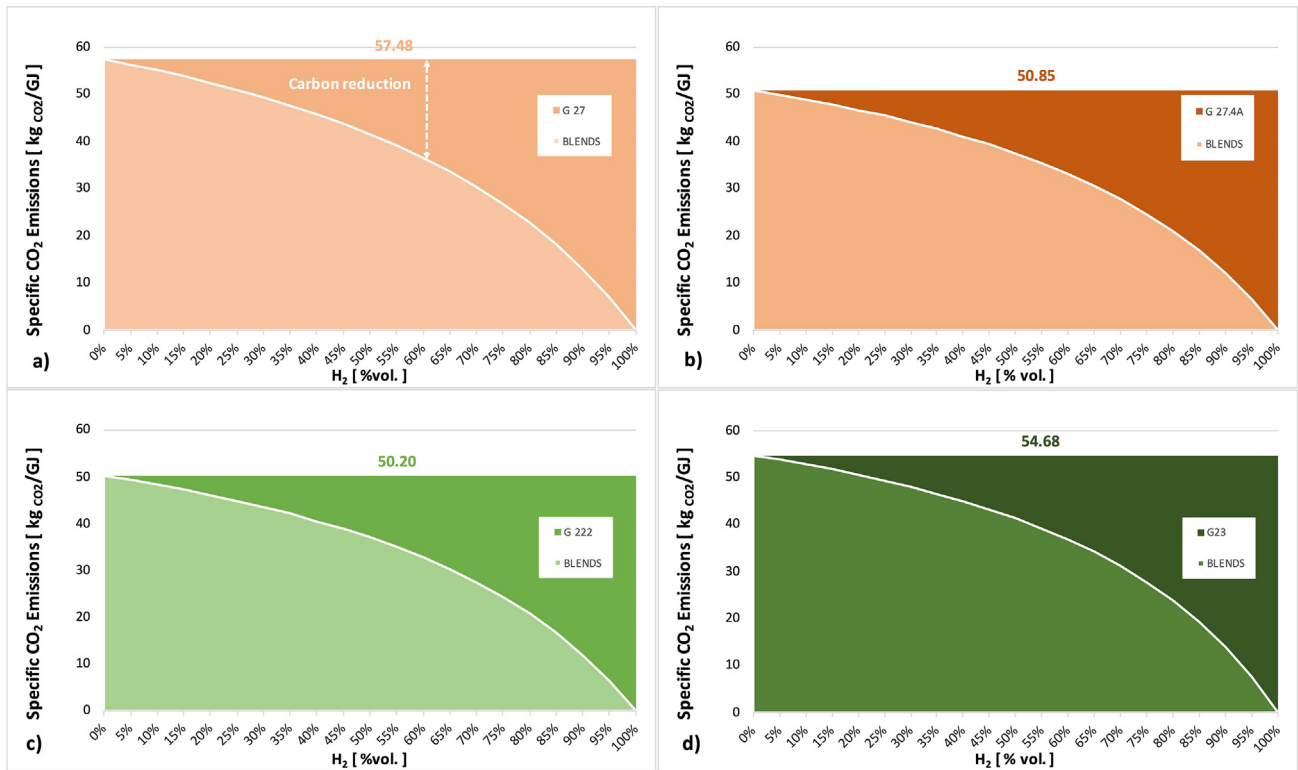

Fig. 6 – CO_2 specific emissions vs. hydrogen fraction for different Natural Gas types: a) G 27; b) G 27.4A; c) G 222; d) G 23.
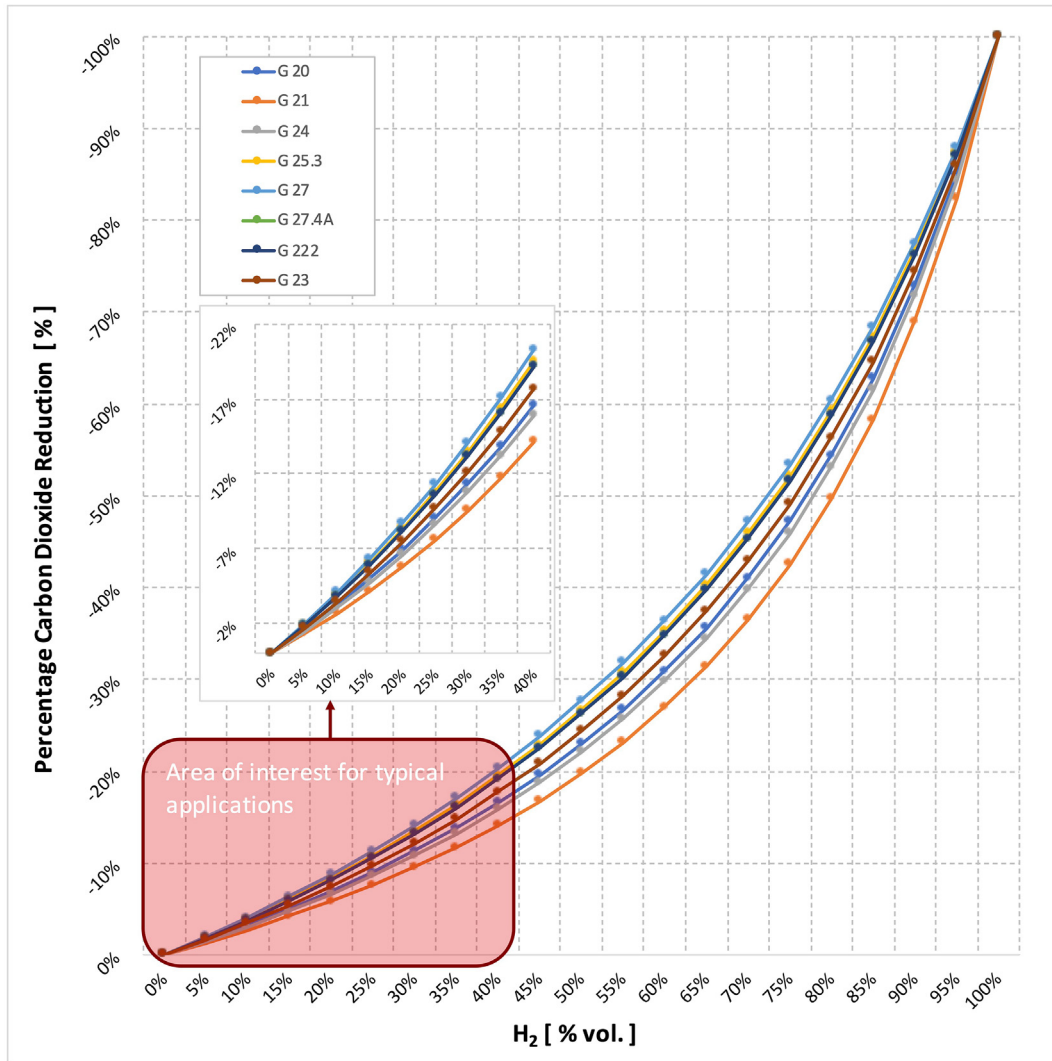
Fig. 7 — Percentage carbon dioxide reduction vs. hydrogen fraction with changes in NG type.

a valid and viable option for greening the Natural gas sector. Although the current energy crisis imposes to rethink and redesign our energy systems in favour of more electrified scenarios, the hydrogen blending is now a necessary step forward to immediately contribute the hydrogen economy rise up. Indeed, all those countries characterised by a strong dependency on NG still have intrinsic barriers to be overcome in order to get high electrification degrees. Therefore, the hydrogen blending represents, in the short term, an environmentally friendly strategy to promote their transition.

Hydrogen blending effects on NG networks

Blending hydrogen into NG pipelines, modifies the some properties of the mixtures, which follows with the decrease in temperature and pressure [23]. Furthermore, the energy density also drops (Wobbe Index), therefore the pipeline pressure

gradient should be higher to keep constant the energy transportation.

As reported in Ref. [65], adding 10% of hydrogen, the Wobbe index decreases by 3%, namely equal to 14.5 kWh/Sm^3. According to the European union regulations, the acceptable WI variations within pipelines is in the range of 12.9–15 kWh/Sm^3 [66], which means that 10% vol. blending could meet those requirements. Based on studies performed on the acceptable blending range, hydrogen content should not exceed 20% vol. since it results in LHV less than 10 kWh/Sm^3, and the mixture does not deliver enough energy [67]. Nevertheless, the safety issues arising from H$_2$NG cannot be neglected.

One of the main features, as mentioned in Ref. [68], is related to the hydrogen leakage from pressurised equipment, which may result in an unexpected ignition due to its chemical properties. That issue hails from the fact that the hydrogen leakage rate is not the same as hydrocarbons [69]. Escaped hydrogen can be hazardous by being in touch with

ignition sources like electricity sparks from equipment, such as closing valves, or electrostatic devices [30].

Other phenomena to be taken into account are related to Joule-Thomson effect. Generally, gases expansion (starting from high pressure towards low pressure) is followed by temperature decrease. However, some gases do not obey such a law beyond the specified temperature and pressure conditions. It is defined as Joule-Thomson (J-T) inversion curve. For hydrogen the maximum inversion temperature, when the pressure is equal to zero bar, is 202 K. It implies that at higher pressure or temperature, hydrogen temperature rises during expansion. Notwithstanding, such an increase is not usually in the scale of air-hydrogen mixture ignition threat. For instance, in the case of hydrogen, by expanding from 100 to 0.1 MPa, a 46 K increase occurs starting from 300 K [70].

Hydrogen effect on degradation in steel pipelines

Injecting hydrogen into Natural gas infrastructures causes the direct contact between hydrogen molecules with steel pipelines and other network installations. Indeed, those components are specifically designed for natural gas operation. The materials degradation occurs when hydrogen atoms enter interspatial spaces [24]. That interaction affects the steel mechanical resistance, and it decreases steel ductility. Such a phenomenon, which is known as hydrogen embrittlement (HE) of steel, is considered as one of the major problems associated to the hydrogen blending. It mainly occurs by following three different mechanisms [34]:

1. adsorption of hydrogen molecules on the pipe surface by the atmosphere which is followed by steep lattice absorption;
2. the hydrogen that entered the lattice can embrittles the steel from inside (Internal Hydrogen embrittlement);
3. Chemical reaction between hydrogen and the surface itself which can result in formation of gaseous methane inside the pipelines.

As a result of embrittlement eventually, micro-pore accumulation and micro crack propagation could be formed in the steel microstructure affecting several steel mechanical properties.

Research studies focused on HE effect on mechanical properties of steep material show significant shortcoming in yield and tensile strength, elongation to failure, area reduction, crack propagation resistance, fatigue lifetime, hardening rate, nano elastic and nano hardness properties [71–74]. By increasing hydrogen fraction in H_2NG mixture, increases also the H_2 partial pressure. Based on the result from an experimental study [75], such a pressure strongly favours hydrogen penetration into the pipeline material and eventually HE. The outcome shows a grave reduction in elongation at failure equal to 38% [76].

Table 5 reveals the mechanical characteristics of ten steel pipes under HE effects. σ_y is the yield stress, σ_{ul} is the ultimate stress, and K_{lc} is the fracture toughness.

The external factors can also affect the level of HE failure. The variation of hydrogen partial pressure can eventually

Table 5 – Mechanical characteristics of ten steel pipes after HE under gas pressure. Source: Ref. [76].

Steel	σ_y (MPa)	σ_{ul} (MPa)	σ_o (MPa)	K_c (MPa $\sqrt{m}$)	K_{IH}/K_c %
1080	414	784	599	111	71
A 516	364	551	457.5	102	68
API 5L Grade B	299	518	408.5	89	74
API5L X42	331	490	410.5	69	46
API5L X46	374	–	187	–	NC
API5L X52	429	597	513	108	50–97
ALI5L X60	422	590	506	142	73
API5L X65	506	611	558.5	180	49.5
API5L X70	566	653	609.5	197	48–95
API5L X80	566	707	636.5	56	6

damage the pipeline as well as environment temperature and flow rate. Such parameters alters hydrogen dissolution which determines the depth of HE inside the pipeline [77]. The application of steel pipelines can be compromised especially when the gas contains amount of H_2S. Sulphide stress cracking (SSC) increases the corrosion risk as far as the mechanical stress and therefore it is considered as one of the major problem of inducting hydrogen into pipelines in sour environments [78]. When the pipeline encounters such conditions, hydrogen atoms participate to steel corrosion process which eventually can diffuse inside the steel itself. That phenomenon is known as Hydrogen Induced Cracking (HIC), which happens by injecting high hydrogen amount into the material. Even if the hydrogen concentration is limited to a few ppm, it can lead to the cracking if the hydrogen critical amount is induced [79].

The effects of hydrogen blending on NG pipelines during different load scenarios was investigated in literature in quasi-static loading testing as well as in the cyclic testing. In a quasi-static loading, the load change in time is considered constant or quite slow, so that it can assume a steady state distribution. Cyclic loading focuses on fluctuations on the gas pressures dealing with hydrogen transport and storage. In cyclic states, hydrogen shows the most degradation in pipelines [24]. Several studies experimentally investigated the hydrogen effect on mechanical properties of steels in both quasi -static and cyclic loading [80]. The testing result shows that hydrogen has not significant effect on the yield and tensile strength of the pipeline [81]. Yet, hydrogen degradation on ductility of steel pipeline has been observed. The authors in Ref. [80] reported the reduction in area at fracture or elongation to fracture in the hydrogen presence.

Hazards and safety issues

The transport of hydrogen via gas networks and the supply of end users with H_2NG blends is associated with potential safety issues. In Ref. [82] the authors summarised the main risks in:

- Gas build-up
- Explosion in enclosures
- Risk from transmission pipelines.

By analysing the gas build-up in a small household room and in a larger room typical of commercial or industrial facilities, similar behaviours were registered. Indeed, no separation of H_2 from the H_2NG blend occurred. In addition, releases at higher flow rates recorded higher gas concentrations, but to a lesser extent than expected [83]. Such values are attributable to floating and ventilation generated from the leakage. Significant concentration values are achieved at $f_{H2,vol}$ above the 70% vol.

Regarding the explosion risk in enclosures, the effects of H_2NG explosion in confined areas are very similar to those caused by pure methane explosion [84], provided that higher $f_{H2,vol}$ than 20% is not employed. Major hydrogen percentages, exceeding the 50% vol., provoke greater overpressure [85], enhancing the hazard [86,87]. Such a vapor cloud explosion overpressure can be mitigated by the venting or by reducing the structural congestion, in order to avoid confinement [88]. On the other hand, the risk hailing from transmission pipelines is directly proportional to the frequency of pipeline failures, probability of ignition and consequences of the fire.

Compared to the natural gas transmission pipelines explosion, the severity of the risk, once the H_2NG blends are used, shifts spatially [89]. Indeed, the hazard is greater in the proximity of the explosion and decreases moving away. In Fig. 8, the likelihood of a person becoming a fatality in a given year is represented.

From charts it emerges how by increasing the hydrogen concentration the hazardous distance is reduced and the increase in risk closer to the pipeline is more significant.

An overview of the required technical upgrades and adaptations of the most common devices for end users fuelled with blends is performed in Ref. [90].

According to the statistical data regarding 120 hydrogen incidents in 1999−2019 analysed by Yang et al. [91], the most accident-prone locations are laboratories, hydrogen fuelling stations [92,93] and hydrogen-related commercial facilities [94]. Notably, those places account for 38.3%, 10.6%, and 9.0% of incidents, respectively. The main causes correlated to the probable hazards are associated to equipment failures, human errors and design flaw, causing property loss, human injuries and fatality in the 41.83%, 10.27%, and 5.32% of cases, respectively. The equipment components mainly involved in the $120H_2$ related incidents regard piping rupture and fitting/valve breakdown. In Ref. [91] the transmission schlieren method and planar laser Rayleigh scattering method are analysed. Moreover, hypothetical scenarios due to hydrogen leakage have been envisaged in a flow chart, as depicted in Fig. 9.

Effects on NG meters

The current natural gas distribution and transmission network, including measuring devices and end user appliances are designed to operate with natural gas properties. Nevertheless, blending hydrogen to natural gas influences each component behaviour. The potential impacts of such mixture to current network should be recognised to prevent any damage to devices and safety issue.

The potential effect of H_2NG on operation of gas meters has been studied experimentally to evaluate whether the long term operation without safety issues is feasible [67]. The authors have examined a test on twelve diaphragm meter durability considering the flow rate at maximum gas meter capacity for 5000 h at gas meter rated pressure. The samples in this experiment were natural gas itself, blended with 0% vol., 5% vol.,10% vol. and 15% vol. of hydrogen. The results show no significant metrological difference in terms of meters error indication between NG and different hydrogen concentration samples. Additionally, no significant damage has been found to risk safe operation as well. Another study [95] came up with the same conclusion reporting the variation less than 0.1% between NG and H_2NG 17%. Conversely, a meaningful difference is observed in the long-term operation of the gas meter. Nonetheless, the authors explained it with the wear of the gas meter internal parts for long term operation and do not considered the hydrogen concentration as an issue [96]. On the other hand, for thermal gas meters the behaviour is not the same exactly. Due to variation in mixture thermophysical values like heating value and density, the maximum permissible error for each device could be violated.

As reported in literature, the thermal efficiency for such devices can be decreased on average of 5% for domestic usages [97]. Moreover, going beyond 10% vol. of blending ratio a recalibration might be required, together with some modifications in the flow meter design. Furthermore, the uncertainty of measuring, especially for billing accuracy, increases as well. For instance, measurement error of 7% is expected for blending ratio equal to 10% vol. Studies performed on ultrasonic gas meters, state that up to 30% vol. of blending has no grave impact in operation [96].
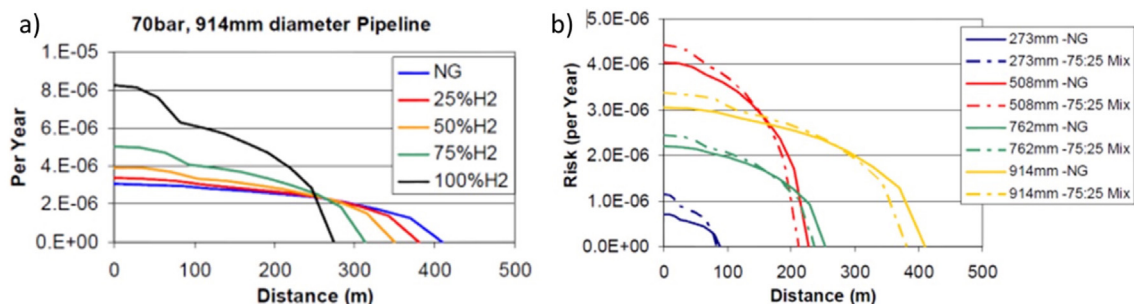

Fig. 8 − Risk to an individual per year: a) as a function of distance from the NG pipeline for a fixed pipe diameter; b) by adding hydrogen to the NG pipelines by changing their diameters. Source: Ref. [82].
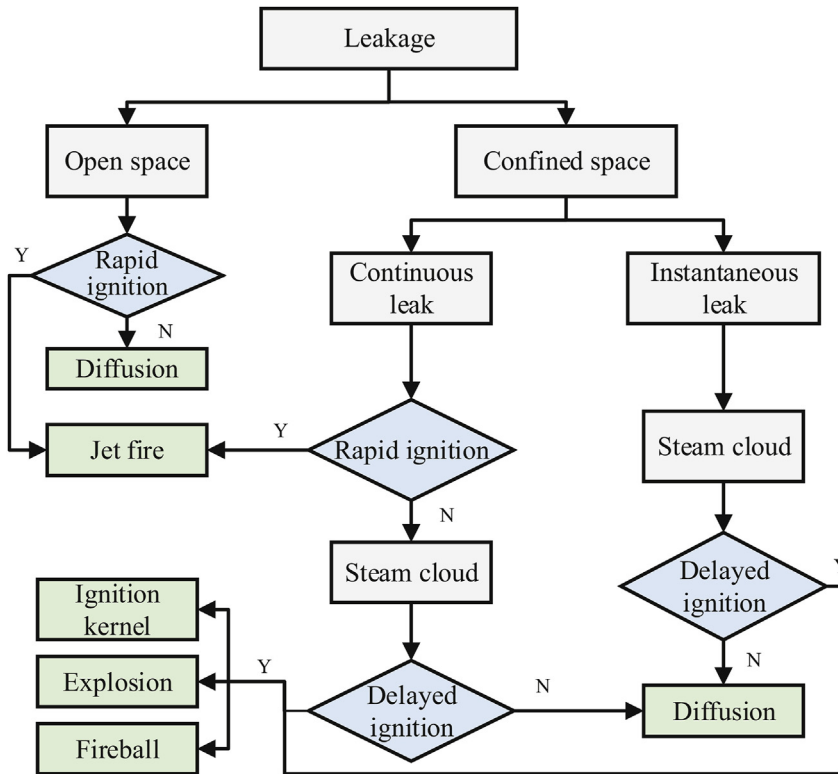
Fig. 9 − Flow chart hazard occurrence due to hydrogen leakage. Source: Ref. [91].

Computational modelling

One of the research topics that has been gained progressive attention in the field of hydrogen blending, is to build up a valid simulation model to predict the gas networks behaviour in the case of sudden changes avoiding potential failures [98,99]. The models are supposed to address multivariable optimization problem of hydrogen blending [100]. Time variation profile of the demand side along with the supply fluctuation, are two significant parameters that invalidates steady state models [101]. Adding to them, multiple injection source causes inhomogeneous and non-constant molar fraction of the mixture. An accurate simulation needs to provide a transient model to describe dynamically pressure and gas flow velocity to keep under control the gas transportation. In general, dynamic characteristics of the system are coupled with the distribution parameters of gas components [102]. To do so, a set of two non-linear first order hyperbolic partial differential equations (PDEs) are needed to describe the mass and momentum behaviour related to the gas flow as indicated in Equations 12) and 13) [103]. Here, p is the pressure of the gas, v is the axial velocity, T is temperature, D is the pipeline internal diameter, ρ is density, M is molar mass, R is universal gas constant, λ is the friction factor, and Z is the gas compressibility factor.

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho v}{\partial x} = 0 \tag{12}$$

$$\frac{\partial \rho v}{\partial t} + \frac{\partial (\rho v^2 + p)}{\partial x} = -\frac{\lambda \rho v |v|}{2D} \tag{13}$$

$$\rho = \frac{pM}{ZRT} \tag{14}$$

Some models also account for the compressibility of real gases to increase the model accuracy [104]. The impact of the hydrogen mass ratio in blending is observed proportional to the overpressure value in transient regime. The periodic evolution of customer demand is considered as the transient regime. Thereafter, the set of governing gas flow equations are solved numerically via COMSOL Multiphysics software.

Another dynamic model [105] is carried out assuming non-constant gas composition, by determining mixing values at each time step and any spatial interval. A finite volume approach is selected to solve the equations by dividing the pipe into discrete elements in which the mixture properties are constant. The case study is an existing medium pressure pipeline of Italian natural gas transport infrastructure. Based on the simulation results, hydrogen has not a significant effect on pressure drop of the mixture since only 0.1% drop off is observed regarding natural gas trend. However, same cannot be said for density profile. In this case, the effect of hydrogen is more obvious. One of the interesting outcomes is density sudden step down due to hydrogen injection.

Table 6 – Screening of the feasible subsurface geological media for underground storage. Source [112].

Storage medium	Reservoir strength	Geochemical and Microbial aspects	Working gas	Cushion Gas Requirements	Overall Effectiveness
Aquifers	Weak	Good	Satisfactory	Weak	Satisfactory
Oil Reservoirs	Satisfactory	Weak	Satisfactory	Satisfactory	Satisfactory
Gas Reservoirs	Good	Satisfactory	Satisfactory	Satisfactory	Satisfactory
Salt Caverns	Good	Good	Good	Good	Good

H_2NG storage

Long-term gaseous storage [106,107] requires capacities of some TWh. The most viable solutions are gas pipelines, salt caverns and fittings (e.g. inoperative mining plants and rock caverns) [36]. Porous rock structures covered with impermeable caprock, as well as the salt rocks, are characterised by large storage capacity. This latter typically amounts to 500,000 m^3 and it is characterised by good gas tightness and operating pressure between 60 bar and 180 bar [29]. All porous rocks require a high share of cushion gas. In the porous rocks the reaction between hydrogen and mineral can occur, leading to the deterioration and depletion of hydrogen and to the clogging of micropores [108,109]. Those gaseous storage solutions don't provide any issues with volumetric hydrogen percentage up to 50% [36]. A potential solution for the H_2NG storage is represented by aquifers. Nevertheless, the latter represents a niche solution due to the presence of sulfidogenic bacteria that are responsible for the hydrogen sulphides generation. Tarkowski et al. [110] analysed the feasibility criteria of subsurface geological mediums for hydrogen, methane, and CO_2 by considering 4 parameters and the overall effectiveness. In detail, the study of the feasible geological media for underground storage has been reported in Table 6. The largest amounts of H_2, CH_4, and H_2NG working gas can be stored in salt caverns [111,112].

Further H_2 and H_2NG short-scale storage solutions include high-pressure gas cylinder [113] or as a liquid at cryogenic temperatures in cryogenic tanks. The storage pressure levels, that overcome the H_2 low volumetric density ensuring adequate volumes, range between 20 and 70 MPa depending on the use. Nevertheless, despite a wide body of literature is dedicated to the high-pressure hydrogen storage tank, H_2NG high pressure storage tank has not been adequately analysed. Indeed, further CFD analysis can represent an opportunity for better evaluate the diffusivity of the CH_4 and H_2 due to their volumetric density difference. The working gas storage as liquid, allows to compensate the hydrogen low volumetric density for storage purpose. Nevertheless, the liquefaction process results energy-intensive due to the methane and hydrogen cryogenic temperatures (respectively 190.56 K and 33.19 K). Moreover, for storage as a liquid, the associated process accounts up to 40% of energy content loss [112].

H_2NG mixtures end-uses

Mixtures in internal combustion engines for transport sector

The transport sector represents one of the most debated and analysed segments for the decarbonisation process and energy saving [114,115]. Hydrogen is a viable solution for decarbonising such a field since it represents one of the most suitable fuels [116]. Indeed, H_2 can be exploited in the fuel cell electric vehicles (FCEVs) and in the most wide spread spark ignition (SI) engines [117,118]. In detail, thanks to its properties, which are outlined in Table 7, the hydrogen addition to conventional HC fuels increases the SI engine's performances and vice versa [119]. Namely, despite the hydrogen high autoignition temperature, the ignition energies of H_2-air mixtures are approximately an order of magnitude lower than HC-air mixtures ones [120].

Due to the lean burn property associated to the H_2, lower equivalence ratios can be exploited, leading to a fuel saving without sacrificing the engine's mechanical performance. The main useful parameters for assessing the engines performance are the fuel conversion efficiency (FCE), power, torque, specific fuel consumption (SFC) and CO emissions. Those latter are affected by the hydrogen rate (H_2% vol.) and injection time (IT) before the top dead centre. The hydrogen presence enhances the flame speed, which stabilizes and accelerates the combustion process, also favouring the Carnot effect owing to increased values of pressure and temperature peaks within the cylinders. Therefore, lower temperature gradients alongside cylinders lead to both CO and HC formation reduction compared with the CNG case. On the other hands, higher NO_x emission occurs when the H_2NG mixtures are burnt caused by the thermal NO_x formation mechanism, which is strongly influenced by the temperature flame, the oxygen concentration and time of exposure [121,122].

Another important factor affecting the SI engines performance is the ignition time (IGT) in the combustion chamber which is also known as spark advance. The IGT strongly impacts the air-fuel ratio and the burned mass fraction [123].

Table 7 – Fuel properties at 25 °C and 1 atm. Source: Ref. [120].

Property	Hydrogen	CNG
Density (kg/m^3)	0.0824	0.72
Flammability limits (volume % in air)	4–75	4.3–15
Flammability limits (Φ)	0.1–7.1	0.4–1.6
Autoignition temperature in air (K)	858	723
Minimum ignition energy (mJ)	0.02	0.28
Flame velocity (m s^{-1})	1.85	0.38
Adiabatic flame temperature (K)	2480	2214
Quenching distance (mm)	0.64	2.1
Stoichiometric fuel/air mass ratio	0.029	0.069
Stoichiometric volume fraction (%)	29.53	9.48
Lower heating value (MJ/kg)	119.7	45.8
Heat of combustion (MJ/kg$_{air}$)	3.37	2.9

Hence, it affects the pollutant emissions along with the misfire and the knock.

Various analyses have been performed on different engines at different conditions and with different parameters. The engine combustion efficiency is defined as the ratio between the actual released energy by the burnt fuel and the fuel mass theoretical energy content over one complete engine cycle. Thus, the fuel conversion efficiency (FCE), as reported in Equation (15), is defined as the ratio of engine power output by the theoretical available power related to the fuel mass.

$$FCE = \frac{P}{\dot{m}_f * LHV_f} \qquad (15)$$

where P is the engine power output (W), $\dot{m}_f$ is the fuel mass flow rate (kg/s) and LHV_f is the fuel Lower Heating Value (J/kg).

Several studies reported the FCE enhancement at higher value of H_2 percentage in the blend. In detail, in Ref. [124] it is highlighted that the FCE raising trend is reduced at higher rotational speed. Referring to the research project reported in Ref. [125], the authors proved that at 4000 rpm the FCE increases as a function of IGT, IT along with the H_2 percentage in the blend. As emerged from data analysis, the IGT effect on the FCE value depends on the IT, and vice versa. Notably, the maximum FCE is achieved at IGT, IT and H_2 equal respectively to 31°, 200 and 30% vol. at 4000 rpm. The specific fuel consumption (SFC) should follow the FCE opposite trend, due to its inverse proportionality with the FCE.

Because of its dependence from the fuel LHV, the SFC is not only affected by the hydrogen addition. Nevertheless, it decreases as the engine rotational speed is higher. Besides, the power output it is not strongly penalised by the hydrogen enrichment, whilst the torque tends to increase as both the hydrogen and engine's speed rise [124]. Zareei et al. [125] demonstrated that the mechanical power increases at higher IT and IGT. Those values are much more predominant than the H_2 percentage in the blend.

An additional crucial factor that determines the engine behaviour is the torque. This latter is characterised by a growing trend as the IGT decreases at each level of H_2 addition. Moreover, the IT value affects the torque as well. The CO response in the engine's performance parameters mirrors the same achieved results for the other parameters. Nevertheless, those optimising values have been obtained having considered the goals at 4000 rpm one by one. The hydrogen percentage in the blend needs to be varied depending on the engine's regime. In detail, the optimal $f_{H2,vol}$ in the blend amounts to 30% as long as 3000 rpm have been set. Thus, that percentage has to be diminished in a stepwise fashion at 20% vol. up to a threshold of 5000 rpm and up. Higher H_2 fractions are needed at lower rotational speed in order to offset the incomplete combustion and the low burning speed. The IGT and IT optimal values vary at different engine's regime.

Fig. 10 shows the five targets optimal value with changes in rotational speed together with the optimised independent variables. The FCE decrease at higher rpm is due to the higher power and the higher efficiency in those operating conditions [125].

Likewise, the driving cycles effect on the SI engine performance. Bauer et al. [126] published a survey dealing with the overall implications of hydrogen blending on the SI engine performance by evaluating two different driving cycles: highway and urban. Furthermore, different engine operating schemes have been analysed. Driving cycle simulations provided the reduction of methane consumption and CO_2 emissions. According to the authors, the application of variable equivalence ratios is the operating strategy most affected by the addition of hydrogen. Furthermore, the analysis showed that for the highway driving cycle, the most suitable value of $f_{H2,vol}$ is between 10.9% vol. and 31.3% vol. In the urban cycle, where the average speed is lower, the ideal f-values are between 10.7% and 37.6%. Anyway, the optimal values for the highway and urban cycle are very close to each other and they are equal to 19.3% vol. and 21.8% vol., respectively.

At leaner equivalence ratios (Φ), the best break specific fuel consumption (BSFC) occurs [127]. Furthermore, the lean combustion limits are noticeably affected by IGT and hydrogen fraction [128].

The authors in Ref. [129] provided an assessment related to the effects of two-step injection of H_2NG on engine performance and pollutants emission. The fuel feeding consists of a first injection of CNG equal to 10% of the total fuel mass into the air manifold (port injection); in the second stage the H_2NG blends at different hydrogen fractions are directly injected into the combustion chamber (direct injection). The experiments showed engine power increase of 2.75% and 3.89% by switching from single-step mode to the two-step one, at the same fuel consumption. That outcome is due to a better mixed charge together with a more complete combustion. Similarly, the engine torque provided in the two-step configuration is improved by the 8% in comparison to the single-step injection mode. Finally, the maximum engine torque is achieved by 30% of hydrogen fraction.

Last but not least are the technical implications on the ICEs associated with the required minimum Methane Number (MN) value.

From a mechanical point of view, it is well known that the lean burning limit as well as the ignition time are strictly related to the major engine operation drawback known as knocking.

Knock is basically an abnormal combustion mode for spark ignited engines in which the unburned mixture reaches sufficiently high pressure and temperature, causing a rapid undesired ignition (or autoignition), before being consumed by the turbulent flame front. As a consequence, the local pressure rapidly raises leading to high pressure fluctuations within the combustion chamber and resulting finally, in a ringing noise called commonly knock. If severe enough, knock can damage the engine by introducing high amplitude stress oscillations and rates of heat transfer.

Due to the hydrogen properties, its addition to NG affects the gaseous fuel ignition time, therefore it significantly increases the knock tendency, especially for enrichments higher than 20% vol.

The MN value is commonly a useful parameter to characterise the knock tendency of different natural gases, taking the difference in knock behaviour between methane and hydrogen to define the extremes of the scale. For that purpose, pure methane is considered as the most resistant whilst the hydrogen the least resistant.
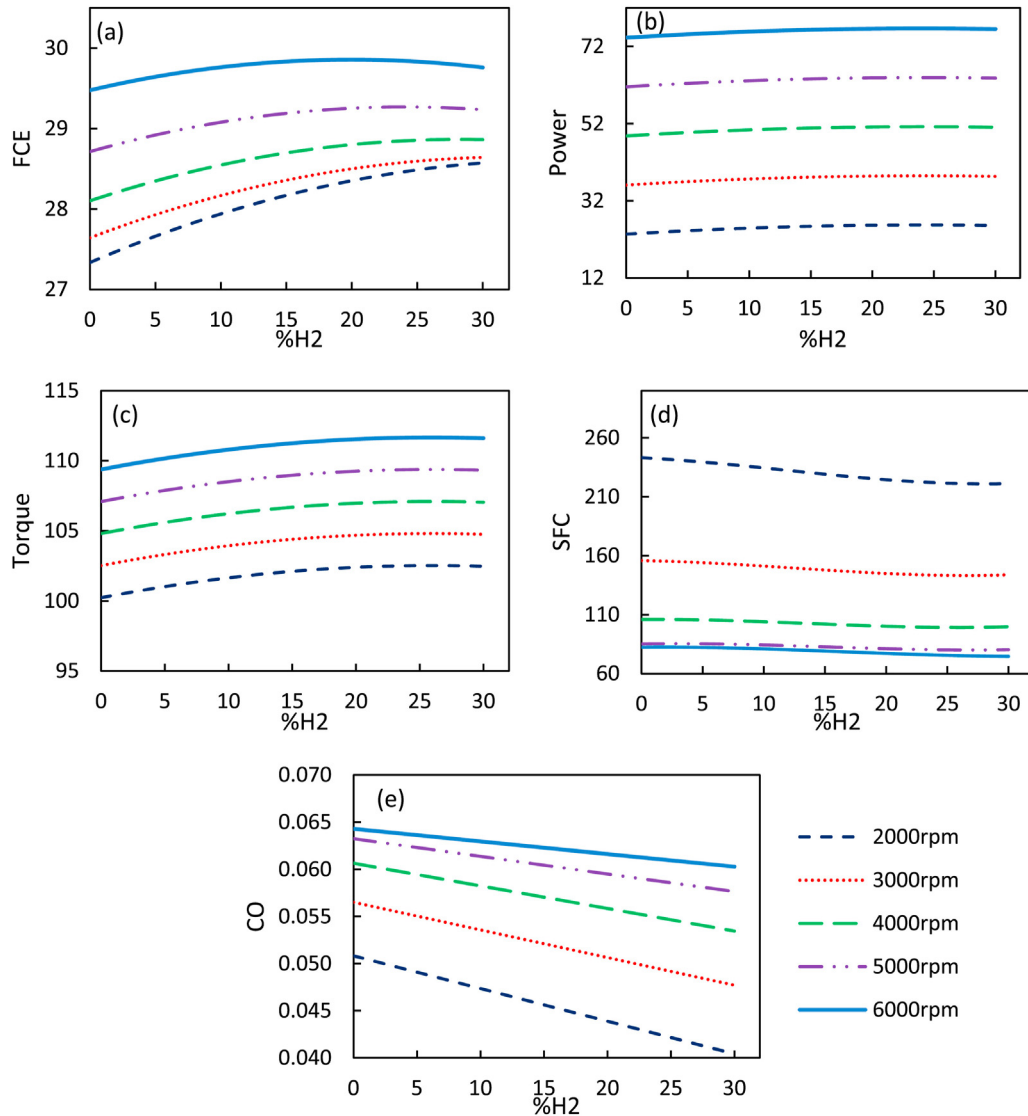
Fig. 10 — Engine performance curves according to % H₂ and rpm variations with constant values of IGT = 23.2, IT = 170. Source: Ref. [124].

After this premise, it is clear that once hydrogen mixtures are used, the relative methane content shrinks and the mixtures' ability to detonate raises, especially for engines having high volumetric compression ratios. Therefore, the gaseous fuel knock resistance and the engine compression ratio are the main parameters to account for in order to make the most proper tuning to maximise the efficiency.

Those two parameters are hence correlated, so the MN is the common rating system to quantify the gas quality and its ability to resist autoignition.

Leiker et al. [130] defined the MN as: "the percentage by volume of methane blended with hydrogen that exactly matches the knock intensity of the unknown gas mixture under specified operating conditions in a knock testing engine. For the range beyond 100 MN, methane-carbon dioxide mixtures were used as reference mixtures. In accordance with

the definition, the MN is 100 plus the percent CO₂ by volume in the reference methane-carbon dioxide mixtures".

Malenshek et al. [131] proposed an empirical linear correlation between MN and compression ratio r_{compr} reading as:

$$MN = 11.438 \cdot r_{compr} - 61.652; \quad R^2 = 0.9766 \tag{16}$$

By that numerical fit it is possible to evaluate the engine critical compression ratio and using it as key parameter for properly designing the gas engines. Nevertheless, the MN method shows a drawback because it does not account for the set-up combustion conditions. Indeed, the MN is typically derived from knock measurements performed on stoichiometrically operating engines. For that reason, it is necessary very often to refer to dedicated inhouse calculation tools, developed by each engine manufacturers, to understand the real MN limit.

Household appliances

Some countries are characterised by an extensive NG network supplying most households. Therefore, some studies in recent years focused on the possibility of fuelling domestic appliances with hydro-methane mixtures [26,132,133]. According to Ref. [134], the threshold limit for running safely domestic end-users without any modifications on commercial versions, is equal to 30% vol. of hydrogen content. Mitigating the flashback risk is crucial to determine such a limit to the hydrogen enrichment. Flashback is generally defined as an uncontrolled upstream propagation of the flame, caused by local imbalances in the gas flow velocity and the flame speed. Substantially, it is a momentary or sustained flame retrogression upstream of the mixing point, occurring usually in the nozzles, torches, or hoses. Indeed, it is always a consequence of a backfire in combination with a gas mixture in parts of equipment due to a reverse fuel flow. That reverse flow can be originated by either improper shutdown and/or startup procedures, or by allowing cylinder pressures to become too low, or by a check valve that is not working properly, depending on the device typology utilised for burning. This is a potentially dangerous situation, particularly if the flame reaches the gas supply hoses and pipes. Those ones

can explode, or in the worst case, the flame can continue into the regulator and into the pipes themselves. However, there are further mechanisms that can lead to an undesirable combustion in the upstream parts of the burner, such as autoignition, combustion instabilities, turbulent flame propagation in the core flow and flame propagation in the boundary layers.

At the same time, it is important to quantify the CO and NO_x emissions since those devices are typically installed indoors. For that purpose, the research project presented in Refs. [125,135] dealt with an experimental campaign on some domestic appliances, whose the main findings are depicted in Figs. 11 and 12. All of the pollutants' emissions concentrations are referred to the exhaust gas volume dry and normalised to a reference oxygen content equal to 0% vol. Table 8 shows the tested devices technical characteristics related to data reported in Figs. 9 and 10.

Higher hydrogen percentage strongly affects the flashback risk, due to the wide H_2 flammability range. If the flashback appears, the flame can retract into the fuel port from the combustion chamber, causing the spillage of the fuel mixture. The enhancement of H_2 fraction in the blend also leads to higher burning velocity [25], weakening the tendency of lifted and yellow flame. The enhanced burning velocity, combined
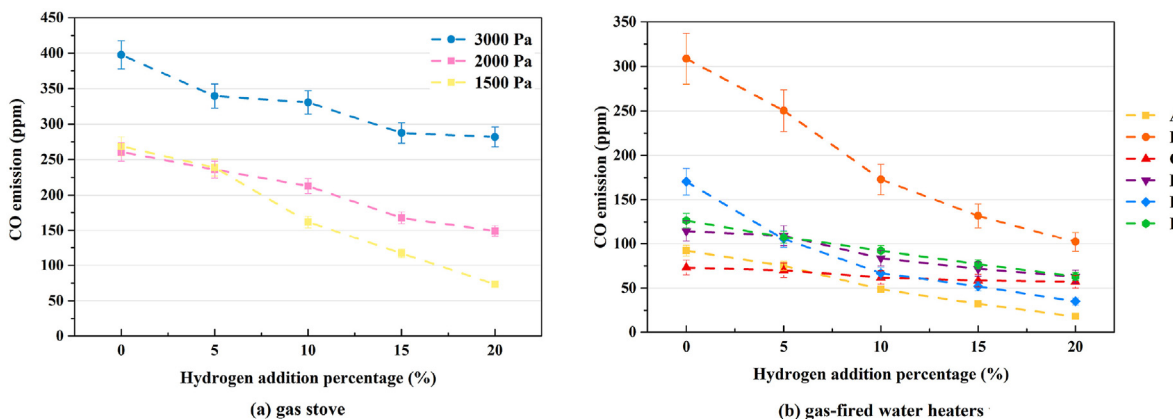

Fig. 11 — CO emission of different hydrogen addition (a) in the gas stove, and (b) in the gas-fired water heaters with 100% rated heat input (A to F represent different types of gas water heaters). Source: Ref. [136].
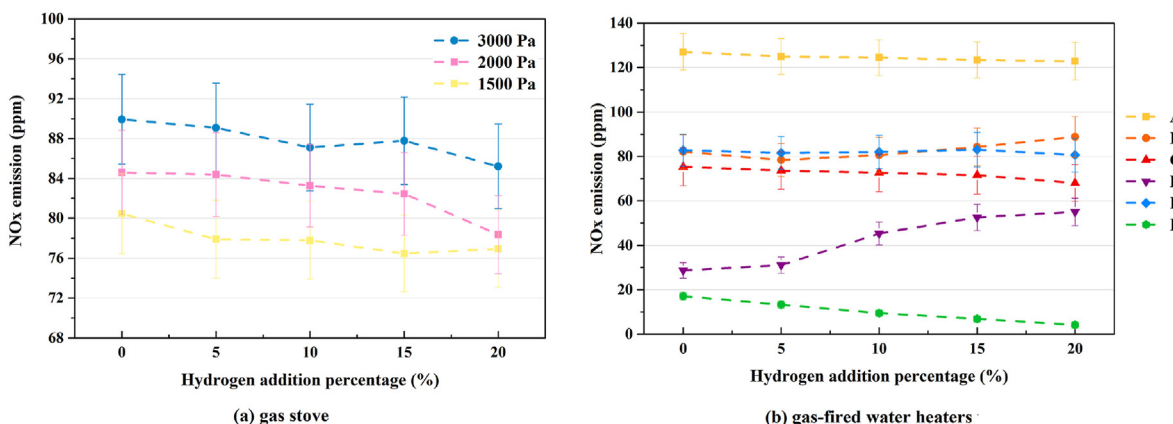

Fig. 12 — NO_x emissions of different hydrogen addition (a) in the gas stove, and (b) in the gas-fired water heaters with 100% rated heat input (A to F represent different types of gas water heaters). Source: Ref. [136].

Table 8 – Design parameters of domestic gas appliances for experiments in Ref. [125].

Test Prototype	Domestic gas Appliance	Model	Rated heat Input [kW]	Hot water rated output [kg/min]
A	Natural exhaust gas water heater	JSD10-B	10	5 ($\Delta t = 25$ K)
B	Forced exhaust gas water heater with AC blower	JSQ24-12H5	24	12 ($\Delta t = 25$ K)
C	Forced exhaust gas water heater with DC blower	JSQ25-13D	25	13
D	Forced exhaust condensing gas water heater with AC blower	JSLQ20-12WL5E2	20	12
E	Forced exhaust condensing gas water heater with DC blower	JSLQ21-13GV56	21	13 ($\Delta t = 25$ K)
F	Full-premixed condensing gas water heater with DC blower and forced exhaust	LL1GBQ21 (SRS 24)	23.8	11.4 ($\Delta t = 30$ K)
G	Gas stove	–	4.2	–

with the unburned mixtures, increases the flashback risk as well, affecting the combustion characteristics and the flame stability. The burning velocity changes slowly when more hydrogen is added up to 50% vol. and it is also affected by the air excess value [136].

For different equipment, once the hydrogen increase the air excess coefficients tend to increase, but the primary and stoichiometric air flow-rate show different trends [137]. Even though the air excess contributes to mitigate the NO$_x$ formation, it reduces the input heat affecting the thermal efficiency and water dew point. This latter is slightly influenced by the hydrogen addition increasing the dew point temperature within 1 °C. In Ref. [136] the effect of the natural gas enrichment with hydrogen was tested and simulated. In Fig. 13 it is possible to see that the NG flame colour appears bluer and brighter than the H$_2$NG one. Moreover, the NG inner flame seems relatively pointed and, after the 20% vol. of hydrogen content the outline gradually assumes the shape of a short ellipsoid. Exceeding the 25% vol. the flashback phenomenon starts to take place. Furthermore, growing the H$_2$ fraction a flame approach to the fuel port occurs, which may lead to the burner surface overheating and malfunctioning [138].

The hydrogen blending provides a reduced volumetric fuel LHV and consequently higher in flow rates are required. Those latter are correlated to the nozzle structure in the burner (d),

gas pressure and gas composition (μ). The heat input (HI) can be calculated by using Equation (17) [136].

$$HI = HHV \cdot 0.0036 \cdot \mu \cdot d^2 \cdot \sqrt{\frac{P}{s}} \qquad (17)$$

where:

- s: mixture relative density;
- HHV: higher heat value [MJ/m^3];
- d: nozzle diameter in the burner [mm];
- μ: gas viscosity coefficient [Pa*s].

From Equation (17) it emerges how the HI is directly proportional to the Wobbe Index under certain pressure conditions. Hence, the heat input shows a decreasing trend as the blended hydrogen in NG increases.

$$K = 0.0036 \cdot \mu \cdot d^2 \cdot \sqrt{P} \quad (K = constant) \qquad (18)$$

$$HI = K \cdot W \qquad (19)$$

Boilers

A wide usage of the H$_2$NG blends is foreseen for the boilers. Nevertheless, a gap in literature about the H$_2$NG blend
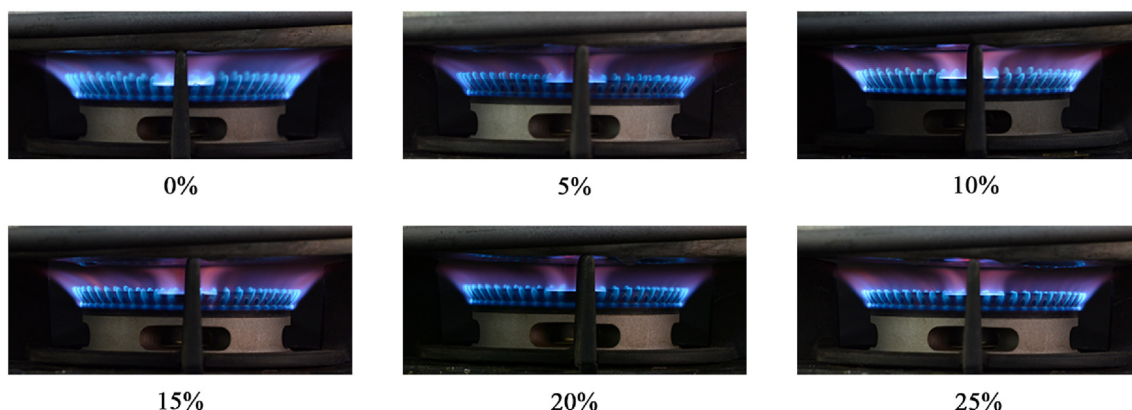

Fig. 13 – Flame image with the increase of hydrogen in the gas stove. Source: Ref. [136].

integration in the standard and condensing boilers have been registered instead of what was published on the H₂NG usage in industrial burners [75]. In Ref. [57] the authors analysed the hydrogen addition effects on the performance of the existing conventional and condensing boilers according to the current standards and regulations. In detail, the authors formulated the percentage sensible heat loss to the stack in accordance with Equations 20) and 21).

$$\frac{P_{loss,sens}}{P_{fuel}} = \left(\frac{K_1}{20.9 - O_2} + K_2\right) \cdot \Delta T \tag{20}$$

$$\frac{P_{loss,sens}}{P_{fuel}} = \left(\frac{K_3}{CO_2} + K_2\right) \cdot \Delta T \tag{21}$$

where:

$$\Delta T = T_{exh} - T_{air} \tag{22}$$

$$K_1 = R_d \cdot \alpha_{st,vol} \cdot 20.9 \cdot \frac{c_{p,exh}}{LHV} \tag{23}$$

$$K_2 = \frac{c_{p,exh}}{LHV} \tag{24}$$

$$K_3 = R_d \cdot \alpha_{st,vol} \cdot CO_{2,th} \cdot \frac{c_{p,exh}}{LHV} \tag{25}$$

In the aforementioned equations, α_{st} denotes the stoichiometric air to fuel ratio, R_d stands for the fuel relative density and $c_{p,exh}$ is the exhaust gas specific heat at constant pressure. From data, it emerged that K_1, K_2 and K_3 values are very sensitive to the volumetric hydrogen percentage [57]. Indeed, the K values are lowered by the H₂ fraction increase. Therefore, with the same recorded exhaust gas temperature the boiler efficiency rises. K_1, K_2 and K_3 are sensitive to the specific heat as well. This latter is affected by the temperature and mostly by the burner combustion set-up and oxygen concentration. By varying the oxygen concentration in a range of 0% vol. −15% vol. the exhaust gas specific heat nonlinearly decreases, while the larger the $f_{H2,vol}$, the higher the $c_{p,exh}$ values are, as depicted in Fig. 14. The maximum reduction, amounting to 9.825%, is achieved for $f_{H2,vol}$ equal to 30% compared to stoichiometric conditions.

The enhancement of hydrogen content in the blend, also, lightly enhances the water dew point temperature at stoichiometric burning conditions, in condensing boilers. Nevertheless, in such burning conditions the available energy per unit volume of fuel decreases, as well as the heating value. Thus, the air excess reduces the dew point, penalising the condensing efficiency [136].

CHPs

Some works have analysed the impact of hydrogen in Combined Heat and Power (CHP) plants. As mentioned previously, hydrogen has a faster burning speed (about 7 times) than the NG one. As a consequence, the laminar flame speed linearly increases with hydrogen concentration [60]. In addition, hydrogen can increase flame temperature, decrease flame dimension which eventually leads to decrease gas emissions such as CO or NO$_x$ [139].
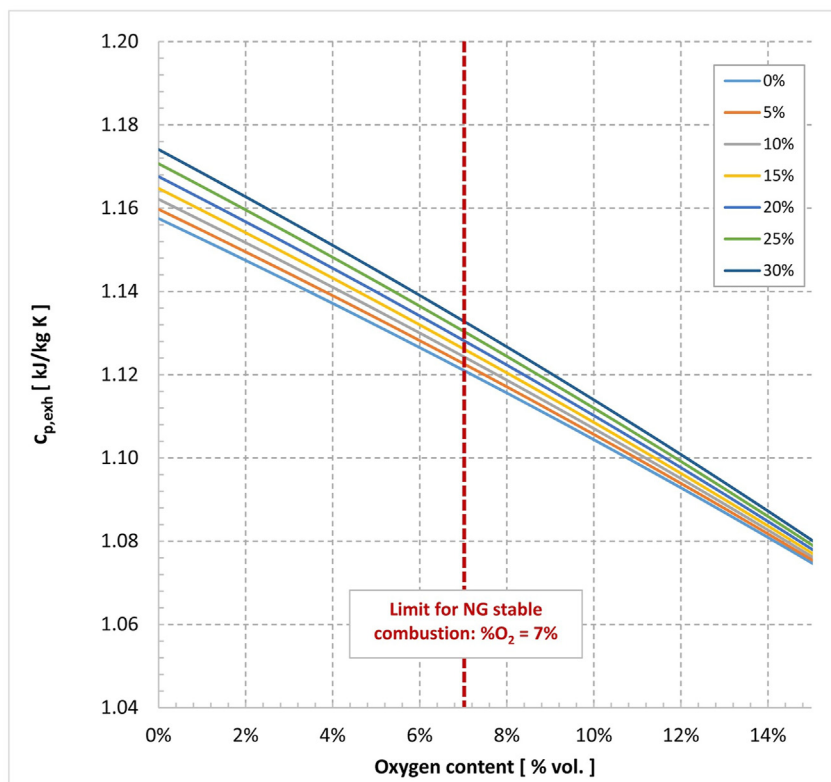

Fig. 14 – Specific heat at constant pressure of exhaust gas vs. oxygen concentration with varying hydrogen fraction. Source: Ref. [57].

In internal combustion engines (ICE), hydrogen blending is turned out to improve the engine thermodynamic efficiency. The authors in Ref. [140] carried out an experimental campaign on the performance of ICE based CHP system fuelled with H_2NG, taking an advantage of free on-site oxygen production as a by-product of water electrolysis (see Fig. 15). They reported a slight increase in power output for H_2 in 5% vol. For higher concentrations up to 20% vol., a higher oxygen flow rate is required in order to increase the power output. Otherwise, the power could be lower even in comparison with NG fuelled scenario. For thermal power recovery section however, higher oxygen flow rate is always needed to ensure higher output. The maximum thermal power is reached at 10% vol. From the environmental point of view, it is found out that hydrogen blending is able to reduce up to 83% of CO concentration.

Another study [141] addressing a CHP system, based on Solid oxide Fuel Cell (SOFC) working at 750 °C was performed to observe the system performance when it was fuelled with NG and H_2. They concluded that by importing mixture instead of methane, although a slight decrease in power output

occurs, the total efficiency including power plus heat increases. However, in compare with conventional system fuelled only with NG, the gas burner needs to be replaced. In Fig. 16, the results of stack efficiency vs methane concentration is illustrated.

Micro gas turbine engine fuelled with hydrogen has also been investigated in literature. Authors in Ref. [142] developed a model on can type combustor analysing the variation of hydrogen/methane blended fuel on combustion properties. The results indicate increase in flame temperature by adding 10% vol. H_2 which leads to higher efficiency. However, further fraction of hydrogen will eventually decrease the flow rate and the input heat which is a negative effect (see Fig. 17). A significant reduction in NO_x emissions has been observed while the progressive CO increase reduces the combustion efficiency. The authors also suggest a modification in fuel injection might be required as well as cooling strategy.

In gas turbines, although with some technical adjustment operation under 10% vol. mixture is feasible, manufacturers advise concentration in range of 1% vol. −5% vol. hydrogen. For instance, a commercial combustor model of GE manufacturer,
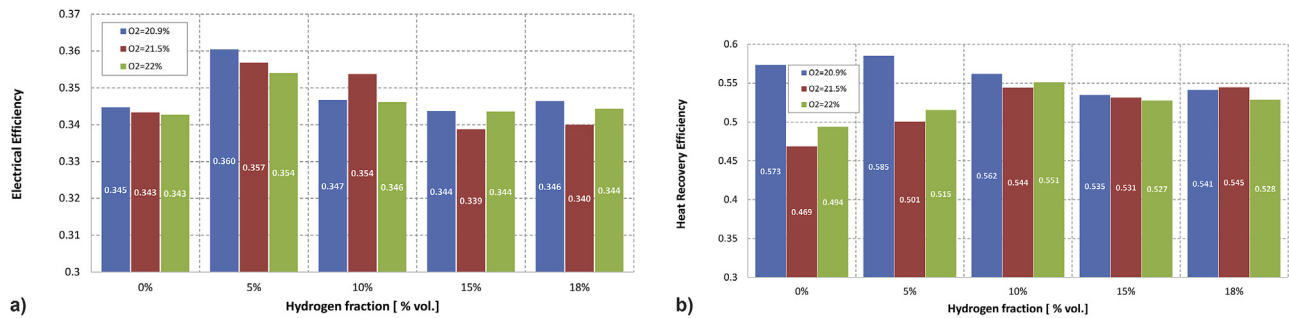
Fig. 15 − Electric and thermal efficiency vs hydrogen fraction in ICE co-generation system [140].
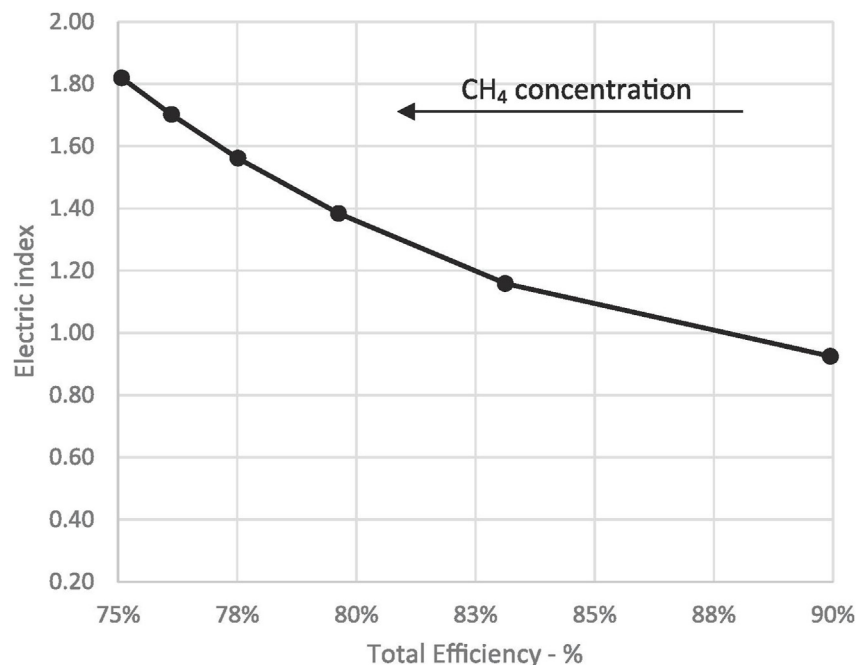
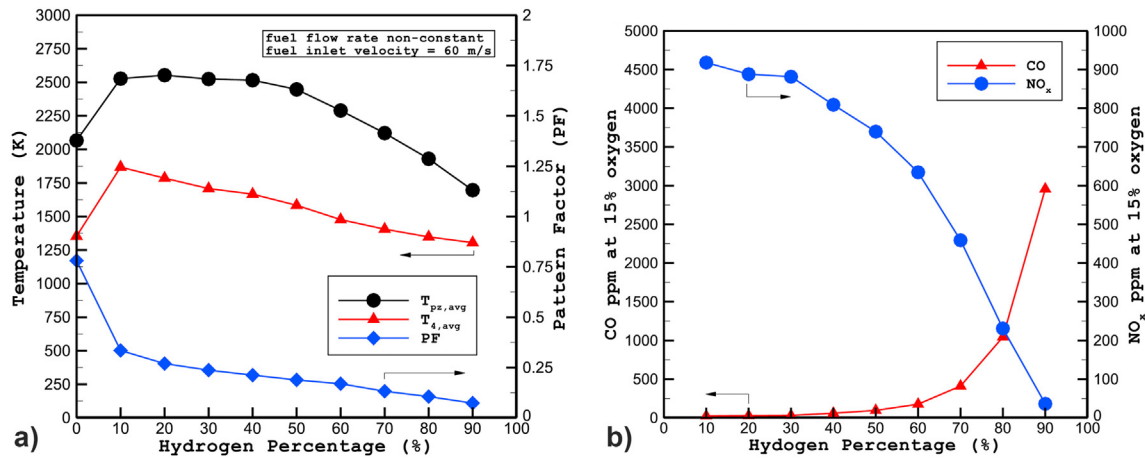Fig. 16 − Efficiency vs CH_4 concentration, Source: Ref. [141].

Fig. 17 – a) Variation of average flame temperature in the primary zone (T_{pz}), combustor (T_4) and pattern factor (PF), b) CO and NO_x variation vs hydrogen fraction [142].

DNL 2.6+ is not designed to operate with more than 5% vol. mixture. For higher volumetric concentration, the manufacturer replace mentioned system by a diffusion flame combustor system MNQC (Multi Nozzle Quiet Combustion) in order to prevent issues like autoignition, flashback, blowout and dynamic instabilities [143]. Another main feature is related to the low blends' energy density. In order to maintain the same power output, the flow rate should increase indeed. In some cases, the adjustment of turbomachinery specially compressor to avoid surge limit is required. The effect of hydrogen on turbomachinery has been discussed in the literature [144,145]. The last major issue is related to the risk of moisture content increase inside the turbine. As a result, the heat flux to the parts of the hot section increases which impacts the lifetime of hardware. In order to address such problem, firing temperature should be decreased [144].

Summary of experimental studies

In the recent years, many studies have been carried out through experimental tests to determine the effects of the mixture on end-users. The results of the main studies have been discussed in the previous sections. In this section, a summary of the survey of experimental studies conducted has been provided. Table 9 summarises some of the experimental studies, highlighting the type of device and the hydrogen fractions.

Economic aspects

Economic aspects of injecting hydrogen into the gas grid have not been widely analysed in the literature.

In Ref. [158], the potential impact of a hydrogen share in NG end-use consumption on electricity and gas prices in Europe has been analysed. In Ref. [50], the authors addressed how the gas grid greening can affect the cost-effectiveness of CHP plants. In that work, a comparison of NG and hydrogen forecasted prices has been provided.

Some work investigated on the costs of H_2NG blends. In Ref. [159], a method for calculating the blend price as a function of energy carrier prices, $f_{H2,vol}$ and gas quality was

Table 9 – Summary of experimental studies on gas-driven end-use devices over the last years.				
Authors	Device	Hydrogen fraction (%vol)	Year	Ref.
Sun et al.	Domestic Appliances	0%–20%	2022	[136]
de Vries et al.	Domestic Appliances	0%–20%	2020	[146]
Zhao et al.	Domestic Appliances	0%–75%	2019	[147]
Zhao et al.	Domestic Appliances	0%–55%	2019	[135]
Boulahlib et al.	Boilers	0%–50%	2021	[148]
Lo Basso et al.	Boilers	0%–35%	2017	[57]
Cellek et al.	Industrial Burner	0%–100%	2018	[149]
Riahi et al.	Co-Axial Burners	15%–20%	2017	[150]
Wu et al.	Co-Axial Burners	0%–50%	2016	[151]
di Gaeta et al.	CHP (micro gas turbine)	0%–100%	2017	[152]
de Santoli et al.	CHP (micro gas turbine)	0%–10%	2020	[153]
Lyu et al.	Blast Furnace	5%–10%	2017	[154]
de Santoli et al.	CHP (ICE)	0%–18%	2020	[140]
Liu et al.	Heavy-duty spark-ignition engine	0%–16.2%	2017	[155]
Du et al.	Gasoline engine	0%–11.9%	2016	[156]
Sforzini et al.	Adsorption Gas Heat Pump	0%–10%	2020	[157]

proposed. Furthermore, the decarbonisation costs as a function of the H$_2$NG blend price was assessed. Thereafter, in Ref. [22], it was discussed how the blend price affects the choice of the best configuration between different building refurbishment strategies.

By harmonising the formulations found in the literature, the energy price of H$_2$NG blends ($p_{H2NG,E}$) can be defined in accordance with Equation (26). That price denotes the cost per energy unit of the mixture, and it is a function of the hydrogen price (p_{H2}), expressed in €/kg$_{H2}$, and the NG price (p_{NG}), expressed in €/MWh.

$$p_{H2NG,E} = \frac{p_{H2}}{LHV_{H2,mass}} \cdot f_{H2,vol} \cdot \frac{LHV_{H2,vol}}{LHV_{H2NG,vol}} + p_{NG} \cdot \left(1 - f_{H2,vol}\right) \cdot \frac{LHV_{NG,vol}}{LHV_{H2NG,vol}} = \left(\frac{€}{MWh}\right) \quad (26)$$

However, existing meters measure gas in Sm^3. Therefore, the effect of hydrogen addition on the volumetric price of H$_2$NG blends ($p_{H2NG,E}$) should also be analysed. That price denotes the cost per unit volume of the mixture and can be calculated according to Equation (27).

$$p_{H2NG,vol} = p_{H2} \cdot \rho \cdot f_{H2,vol} + p_{NG} \cdot \left(1 - f_{H2,vol}\right) \cdot LHV_{NG,vol} = \left(\frac{€}{m^3}\right) \quad (27)$$

In Ref. [22,159], the concept of overprice was also applied to quantify the price increase due to the hydrogen addition. The Energy Overprice (EOP) can be defined according to Equation (28).

$$EOP = p_{H2NG,E} - p_{NG} = \frac{p_{H2}}{LHV_{H2,mass}} \cdot f_{H2,vol} \cdot \frac{LHV_{H2,vol}}{LHV_{H2NG,vol}} + p_{NG}$$
$$\cdot \left\{ \left[\left(1 - f_{H2,vol}\right) \cdot \frac{LHV_{NG,vol}}{LHV_{H2NG,vol}} \right] - 1 \right\} \quad (28)$$

Furthermore, the Volumetric Overprice (VOP) can be computed according to Equation (29).

$$VOP = p_{H2NG,vol} - p_{NG,vol} = p_{H2} \cdot \rho \cdot f_{H2,vol} - p_{NG} \cdot f_{H2,vol} \cdot LHV_{NG,vol} \quad (29)$$

In Fig. 18, the H$_2$NG blend price by energy as a function of hydrogen price and volumetric fraction, in two different NG price scenarios, has been depicted. In those scenarios, the gas price has been set equal to 30 €/MWh and 80 €/MWh, respectively. Furthermore, in Fig. 19, the volumetric price of H$_2$NG blend as a function of hydrogen price and volumetric fraction has been depicted in the same NG scenarios.
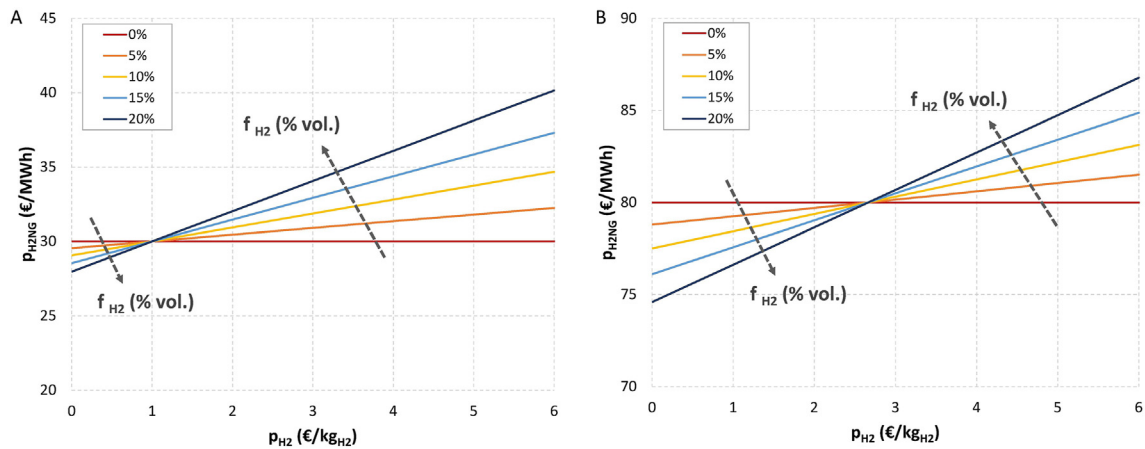

Fig. 18 – Energy price of H$_2$NG blend as a function of hydrogen price and volumetric fraction: A) NG price equal to 30 €/MWh; B) NG price equal to 80 €/MWh.
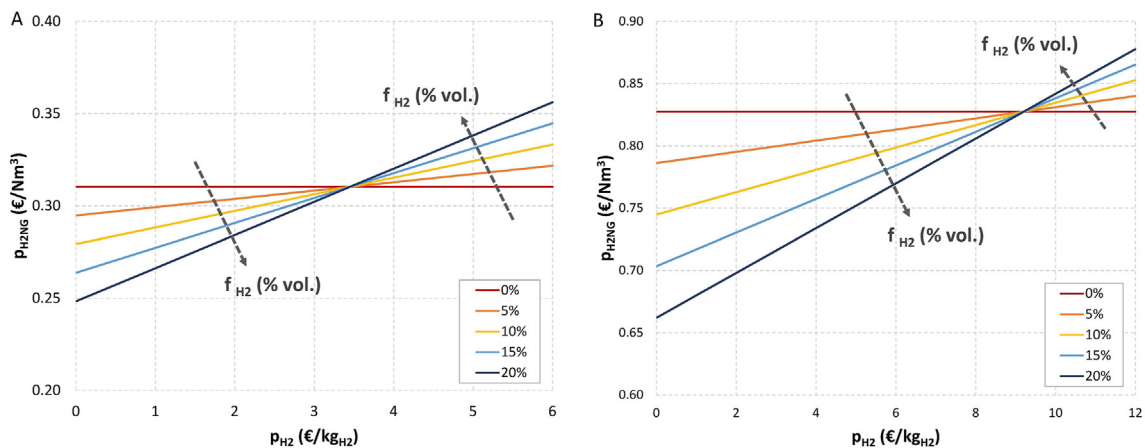

Fig. 19 – Volumetric price of H$_2$NG blend as a function of hydrogen price and volumetric fraction: A) NG price equal to 30 €/MWh; B) NG price equal to 80 €/MWh.
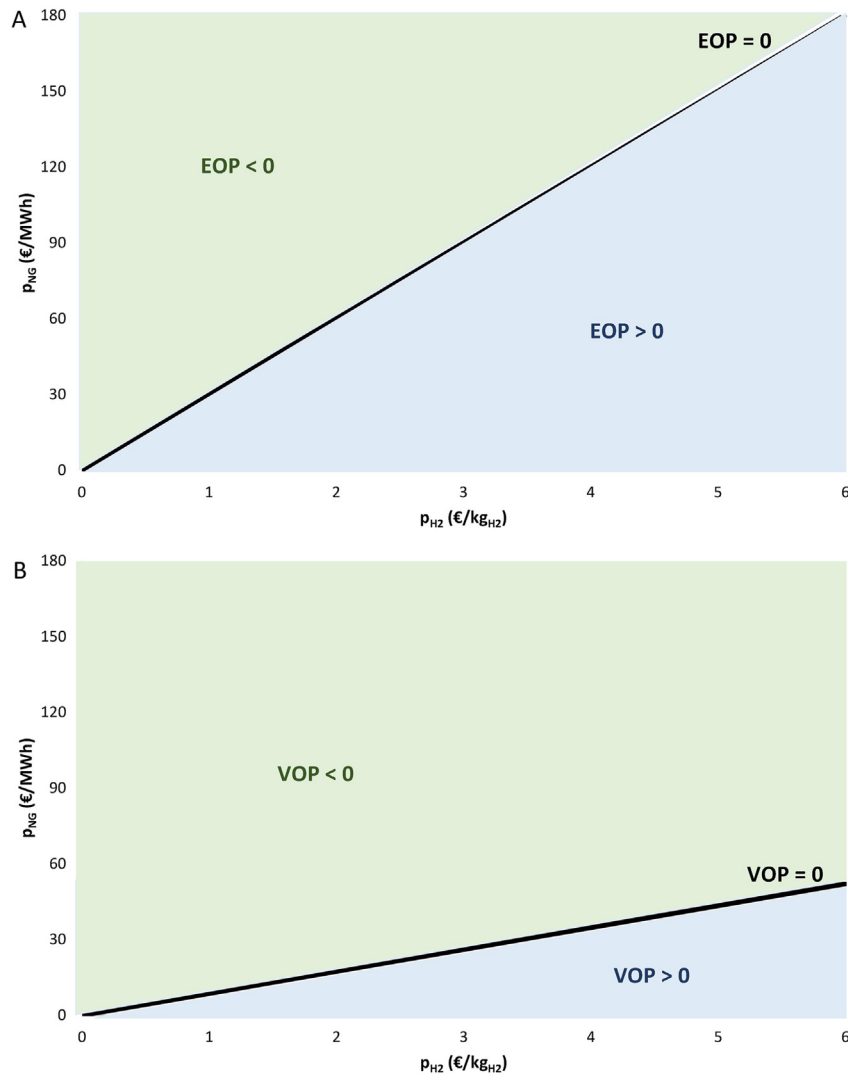
Fig. 20 — a) energy overprice as a function of NG and hydrogen prices; b) volumetric overprice as a function of NG and hydrogen prices.

It can be noticed that there is a value of hydrogen price leading to an EOP equal to zero. That value represents the price for which the hydrogen addition in the mixture does not cause a change in the H_2NG blend price. Furthermore, hydrogen prices associated with null EOP or VOP values do not depend on the volumetric fraction of hydrogen and are exclusively a function of NG prices.

EOP and VOP values, as function of both NG and hydrogen prices, have been depicted in Fig. 20.

The graphs show how the energy carrier price pair results in an overprice greater than, less than or equal to zero. For the same gas prices, a lower hydrogen price is needed to obtain an EOP equal to zero than what is needed to obtain a VOP equal to zero.

This is due, as shown in Section Power-to-Gas Concept, to the reduction of volumetric LHV as $f_{H2,vol}$ increases. Indeed, balancing the volumetric price does not account for the fact that it is necessary to increase the total volume of blend consumption to have the same released energy. Yet, the common metering of natural gas is based on volumetric and

not energy parameters. Therefore, fluctuations of hydrogen content over the year will make incomplete the information required for correct energy billing in the next future.

Such issues are not extensively addressed in the literature and should be further developed by focusing on new smart gas metering and on the potential economic impact on end users.

Conclusions

It is well recognised how hydrogen is going to play a pivotal role into the energy systems decarbonisation pattern for the next future. In this framework, the Power-to-Gas strategy can be considered as a viable bridge solution for the hydrogen wide deployment in the short medium term. Specifically, the blending with natural gas offers a unique opportunity to figure out immediately several technical issues associated to the hydrogen storage and delivery infrastructures.

The concluding remarks of this survey can be outlined as follows:

- A unique and common technical standard, at European level, dealing with the maximum acceptable hydrogen fraction into NG networks is still lacking. Indeed, each EU member State has its own technical standards and limits, therefore in some countries such as Italy, Wobbe Index reductions higher than 3% are not allowed. It entails that only hydrogen fraction lower than 5% vol. continues to meet those requirements, whilst in other countries blends at 10% vol. are already feasible.

- the hydrogen enrichment affects the blends energy density as well as their carbon intensity values. The former, is crucial for transmission features, entailing higher pressure into the NG mains to transfer the same energy amount; the latter, is useful for the NG grid greening process, on one hand shrinking the carbon footprint, on the other hand, potentially decreasing the NO_x emissions, whether ultra-lean combustions were properly set up on the appliances.

- From a mechanical point of view, the steel pipes degradation due to the hydrogen embrittlement has been extensively studied in literature. Anyway, it is possible to conclude that hydrogen has not significant effect on the pipelines yield and tensile strength; nevertheless, the hydrogen degradation on ductility of steel pipeline was observed.

- A research topic, which was widely addressed by scientists, consisted of analysing the internal combustion engines behaviour for vehicles when they are fuelled with H_2NG. In that case, it emerged how the best hydrogen fraction to use ranges in 20% vol. − 30% vol. Moreover, in order to optimise the vehicle performance, multi rails systems were strongly recommended as feeding system, instead of blending hydrogen upstream or in single port injection. Thus, several authors suggested using variable hydrogen percentages when the engine rotational speed changes so as to find a trade-off solution among low pollutants emissions and vehicle autonomy.

- Only in this last decade the H_2NG effects on both stationary power and heat generation were investigated. The main outcomes demonstrated that in CHP applications it is possible to get energy gains in terms of better efficiency values, while in condensing boilers higher latent heat fractions can be recovered owing to the increased water content within the exhaust gas. As regards the gas stoves, the heat input tends to lessen as the hydrogen fraction increases due to the higher relative equivalence ratio. Anyway, exceeding 25% vol. of hydrogen fraction is not recommended since flashback conditions can occur.

In the end, the authors have identified a literature gap dealing with the long-term blends storage systems (i.e. pressurised vessels), real time mixing devices, H_2NG refuelling stations and components reliability assessment on demo sites. At the best of the authors knowledge, those topics could represent the next research challenges to cope with to overcome the current barriers in taking the first concrete step towards the concept of "hydrogen for all".

Several efforts, from both scientific community and industry, have been made in this last two decades, for transforming the vision of a hydrogen economy from a pure concept into reality. To do so, technologies readiness level must be still improved day by day. In such a way, it will be possible to increase the number of installations for effectively producing green hydrogen on large scale as well.

The injection of hydrogen into the gas grid is the most handy-forward means to pursue that ambitious and challenging objective in the forthcoming energy transition phase. Moreover, the recent geopolitical and energy market situation demands urgent actions to get to higher energy independence degree from fossil fuels as soon as possible.

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.

Nomenclature

P	Power (kW)
E	Annual energy consumption (MWh/yr)
ρ	Density (kg/Nm^3)
T	Temperature (°C/K)
p	Pressure (Pa)
D	Diameter (m)
υ	Axial velocity (m/s)
M	Molar mass (g)
A	Area (m^2)
α	Stretch rate (1/s)
L_b	Markstein length (m)
m	Mass (kg)
$\dot{m}$	Mass flow (kg/s)
R	Universal gas constant (N.m/(kmol.K))
Z	Compressibility factor
LHV	Low heating value (MJ/kg)
LHV'	Low heating value (MJ/Nm^3)
$α_{st}$	Stoichiometric air to fuel ratio by mass (kg$_{air}$/kg$_{fuel}$)
$α'_{st}$	Stoichiometric air to fuel ratio by volume (Nm^3$_{air}$/Nm^3$_{fuel}$)
$f_{H2.vol}$	Volumetric hydrogen fraction
$[CO_2]_{th}$	Carbon dioxide volume concentration (% vol)
$[CO]_{th}$	Carbon monoxide volume concentration (% vol)
λ	Ratio of air to fuel
φ	Equivalence ratio
WI	Wobbe index (MJ/Nm^3)
H_{vol}	Volumetric low heat value (MJ/Nm^3)
$S_μ$	Laminar burning velocity (m/s)
S_n	Stretch flame velocity(m/s)
r_u	Radius of flame photograph
$σ_y$	Yield stress (MPa)
$σ_{ul}$	Ultimate stress (MPa)
k_{cl}	Fracture toughness (MPa $\sqrt{m}$)
R_d	Fuel Relative density (kg/Nm^3)
$p_{H2NG,E}$	Energy price of H_2NG mixture($\frac{€}{MWh}$)
$p_{H2NG,vol}$	volumetric price of H_2NG mixture($\frac{€}{m^3}$)

*Subscript*s

st	stoichiometric
μ	laminar
el	Electricity

th	Thermal
f	fuel
vol	Volume
y	yield
ul	ultimate
b	burned
u	unburned
E	energy

Abbreviations

RES	Renewable energy sources
CO_2	Carbon Dioxide
H_2	Hydrogen
PtG	Power-to-Gas
H_2NG	Hydrogen Enriched Natural Gas
NG	Natural Gas
CNG	Compressed Natural Gas
HCNG	Hydrogen enriched compressed natural gas
PEM	Proton exchange electrolyzer
SOEC	Solid oxide electrolyzer
FCEVs	Fuel cell electric vehicles
SI	Spark engines
CCHP	Combined Cooling Heat and Power
CHP	Combined Heat and Power
ICE	Internal Combustion Engine
EOP	Energy overprice
VOP	Volumetric overprice
HE	Hydrogen embrittlement
SSC	Sulphide stress cracking
HIC	Hydrogen induced cracking
FCE	fuel conversion efficiency
SFC	specific fuel consumption
IT	Injection time
IGT	ignition time
BTDC	before top dead centre
PDEs	Partial differential equations

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