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BLENDING HYDROGEN WITH NATURAL GAS/ BIOMETHANE AND TRANSPORTATION IN EXISTING GAS NETWORKS

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The existing European Union (EU) natural gas network provides large capacity to integrate renewable (RGs) and low-carbon gases. Today, hydrogen contributes only a few percent to Europe's energy consumption and is almost exclusively produced from fossil fuels and used in the industry. Nevertheless, hydrogen has a significant role to play in emission reduction in hard-to-decarbonize sectors, in particular, as a fuel in transport applications and as a fuel or feedstock in certain industrial processes (steel, refining or chemical industries, the production of "green fertilizers"). Carbon dioxide (CO_2) in reaction with hydrogen can also be further processed into synthetic fuels, such as synthetic kerosene in aviation. In addition, hydrogen brings other environmental co-benefits when used as fuel, such as the lack of air pollutant emissions.

However, in transitional phase from fossil to RG, namely, renewable or green hydrogen, natural gas/biomethane and hydrogen blends, are needed to gradually replace natural in existing gas transmission and distribution networks. The gas networks are believed to be able to use natural gas/biomethane and hydrogen blends with 5–20 % of hydrogen by volume. Most systems and applications are able to handle it without a need for major infrastructure upgrades or end-use appliance retrofits or replacements. The promotion of hydrogen network such as

European Hydrogen backbone (EHB) is gaining momentum in Europe. To decarbonize the natural gas grids, the threshold of hydrogen in the existing grid systems must be increased, which can be done by means of wider natural gas/biomethane and hydrogen blending and simultaneous transportation in currently operational gas networks.

Keywords: *hydrogen, natural gas, biomethane, gas infrastructure, gas blends*

1. INTRODUCTION

Hydrogen is a colourless, non-toxic, odourless and tasteless gas that usually exists as a two-atom molecule. Hydrogen is the most common element in the universe, accounting for around 90 % of its mass and around 73 % of the visible universe's mass [1]. Hydrogen has three naturally occurring isotopes: hydrogen (^{1}H), deuterium (^{2}H) and tritium (^{3}H). Each has one proton and a different neutron count. Hydrogen has no neutrons, deuterium has one and tritium has two [2], [3]. Hydrogen is not usually found in pure form because it bonds easily with other elements. It is also the lightest known element with a density of 0.08988 grams per litre (gr/l) at 1 bar, and, consequently, the lightest known gas (density: 0,089 kg/m^3; relative density relative to air: 0.0695).

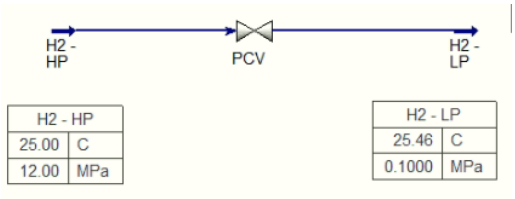
Hydrogen is gaining popularity very rapidly as an alternative source of clean fuel that can be used efficiently and widely with natural gas or biomethane, thus reducing greenhouse gas emissions (GHG) in several segments of the energy sector as well as energy-intensive industrial processes. Many companies plan to use hydrogen as part of their GHG reduction strategy, and, therefore, various natural gas/biomethane and hydrogen blending options and related challenges are being explored both at the industry level and within the framework of cooperation between industry and scientific institutions.

Hydrogen has several important properties that may affect its use in the energy sector:

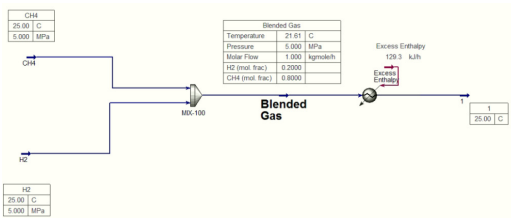
- it connects with oxygen, creating water that is absolutely necessary for life processes and is not toxic;
- it has a high energy content per weight (almost three times higher than petrol), but the energy density per volume is quite low at standard temperature and at 1 ba pressure. The volume energy density can be increased by storing hydrogen at elevated pressure or by storing at extremely low temperatures as liquid;
- hydrogen is highly combustible; only a small amount of energy is needed to ignite it. It also has a wide range of flammability, meaning it can ignite forming 4 to 74 % of the air volume [4];
- hydrogen burns with a light blue, almost invisible flame, making hydrogen fires difficult to spot in daylight [5];
- combustion of hydrogen does not result in emissions of CO_2 and sulphur compounds. Under certain conditions, this may result in emissions of nitrogen oxides (NO_X) [6];
- hydrogen can be obtained from a wide range of sources, including renewables ones (RES) [7].

In order to make the simultaneous transport and use of natural gas, biomethane and hydrogen as safe as possible, it is necessary to take into account certain specific characteristics of hydrogen, such as:

- under standard conditions, hydrogen has a negative Joule–Thomson coefficient. This means that, unlike many other gases, hydrogen warms up slightly after expansion (pressure reduction) [8];



- hydrogen and methane have a negligible blending enthalpy that produces an unideal temperature. The figure below shows the excessive enthalpy of blending. In this case, hydrogen and methane are blended at 25 °C and the gas blend temperature is 21.6 °C instead of 25 °C, which would be expected [8].



Developing renewable or green hydrogen, known as "renewable fuels of non-biological origin", is a priority for the EU. It plays an important role in decarbonizing these sectors of the economies of the EU Member States, where other alternatives could be impossible or more costly. It can be used to replace fossil hydrogen in transport and industrial processes and to create new industrial products such as "green fertilizers" and "green steel" [9], [10].

2. THE EU's HYDROGEN OUTLOOK

In 2020, the European Commission (EC) endorsed a hydrogen strategy for a climate neutral Europe, defining the conditions and actions for integrating clean hydrogen into the energy sector and the economy as a whole, and setting a green hydrogen production target by 2030. The strategy also notes that the introduction of renewable hydrogen into the existing gas supply network may be considered as the first step towards decarbonization of the EU's gas supply sector [11], [12]. Some EU countries have even set a hydrogen percentage target for blending with natural gas and biomethane into the existing gas networks.

As for 2022, hydrogen accounted for less than 2 % of Europe's energy consumption and was mainly used to produce chemicals such as plastic and mineral fertilizers. The breakdown of hydrogen consumption by industry in the EU Member States in 2019 is shown in Fig. 1. 96 % of this hydrogen came from fossil sources, namely natural gas, resulting in significant CO_2 emissions. To change the situation, the EC proposed to significantly increase a production potential of renewable hydrogen by producing 10 million tonnes (Mt) of it by 2030 and importing at least the same amount.

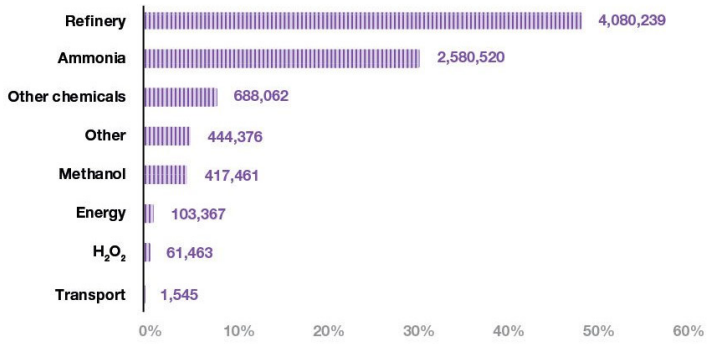


Fig. 1. Hydrogen consumption in the EU Member States (2019, by sector).

The *REPowerEU* framework, on the other hand, offers an updated vision for a more ambitious target of 15 Mt for the production and transport of renewable hydrogen, in addition to the 5.6 Mt already foreseen for *Fit-for-55* package, which are well above the EU hydrogen strategy targets. The new objectives require rapid acceleration of the development of integrated gas and hydrogen infrastructure across Europe, and the EHB initiative has developed such a framework program for 2035. It includes a vision of a hydrogen transport network of around 53 000 km in the EU by 2035 with significant potential for further growth and expansion [13]. Since the initial presentation of the EHB framework program, 31 countries in total have joined the initiative and the planned hydrogen transmission network has increased 110% in length. The 2040 framework programme provides for an investment of between 80 and 143 billion euros (EUR) in the development of a hydrogen transmission network of around 53 000 km. About 60 % of existing natural gas transmission pipelines are expected to be adapted to transport hydrogen, while about 40 % of the pipelines, including underwater ones, will be newly built.

EHB experts estimate that transporting hydrogen 1000 km by land pipeline would cost an average of 0.11–0.21 EUR/kg, making the piping system the most cost-effective solution for long-range transportation of large-scale hydrogen. On the other hand, if hydrogen were transported exclusively through underwater pipelines, the costs would be around EUR 0.17–0.32 per kg/1000 km [14].

There is currently no common technical and legal framework in the EU for the acceptable percentage of hydrogen for transportation and distribution of natural gas/biomethane and hydrogen blend in the public gas supply network. The permitted proportion of hydrogen in a gas blend in gas transmission networks varies from one EU Member State to another. For example, only 0.5 % is allowed in Sweden, 4 % – in Austria and Switzerland, 5 % to 10 % – in Germany (depending on the availability of gas infrastructure). On the other hand, it is permissible to introduce a gas blend with a hydrogen content of up to 12 % into the Dutch gas supply network.

In Latvia, in accordance with Cabinet of Ministers Regulations no. 567 "Regulation on the requirements for the introduction and transportation of biomethane and liquefied natural gas converted into a gaseous state into the natural gas transmission and distribution system", the proportion of hydrogen in the natural gas or natural gas/biomethane blend can be from $\leq 0.1 - \leq 2$ %. However, the highest indicated level can be reached only, if hydrogen is injected into the natu-

ral gas distribution or transmission system, which is not directly related to deliveries to other countries or the Incukalnas underground gas storage (UGS) facility [15]. It should be noted that the complete physical separation of one part of the transmission or distribution system of the country or region may not only be technically difficult, but in some cases physically impossible. Therefore, before deciding on the possibilities of increasing the hydrogen content in the Latvian gas supply system, it is also necessary to agree on the removal of the above-mentioned restrictions.

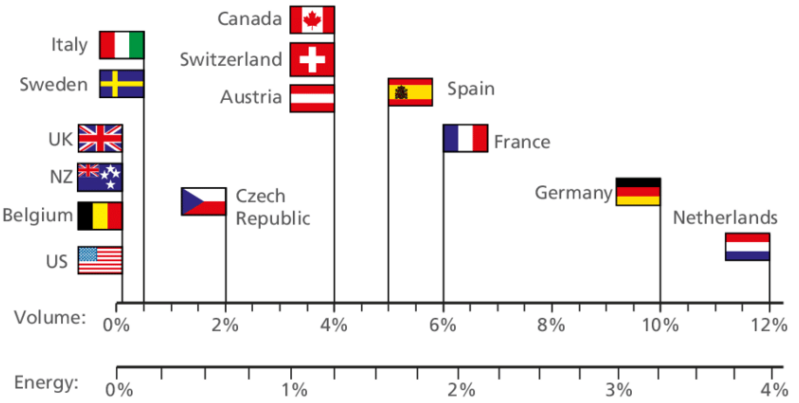


Fig. 2. Share of hydrogen in natural gas/biomethane blend in some countries (2023).

Preliminary studies carried out by the European Network of transmission system operators for gas (ENTSOG) and other organisations have shown that the transport of a natural gas and hydrogen blend is possible without modification of the pipeline, provided that the mass of hydrogen in the gas remains sufficiently low. According to one of the reports, it is possible to introduce up to 2 % of hydrogen "by default" into the gas supply system without making complete technical improvements [16]. Higher hydrogen concentrations, regardless of the network pressure regime, may require some infrastructure adjustments.

This need is linked to different physical and chemical characteristics of hydrogen and natural gas/biomethane, as blending hydrogen with natural gas/biomethane may affect:

- security of gas supply and increase the risk of gas leakage, as potential hydrogen leakage can be much faster and more voluminous than natural gas/biomethane leakage due to higher hydrogen leakage speeds than natural gas/biomethane (especially in high pressure mode);
- the integrity of the pipeline as hydrogen can cause metal fragility of the pipelines (hydrogen-induced cracking) or even damages of polyethylene pipes (especially in high pressure mode) [17];
- gas quality because the addition of hydrogen to natural gas changes the combustion properties and calorific value of the gas, which may directly affect the final consumption sector [18].

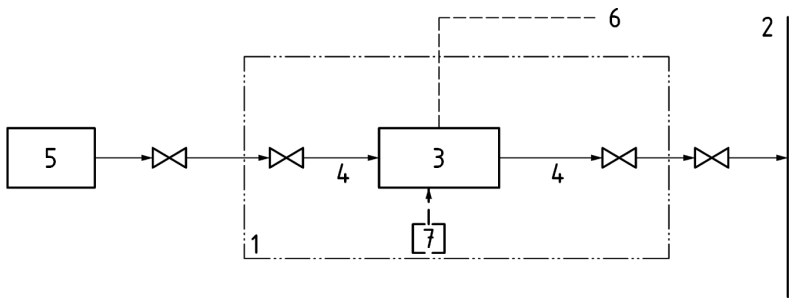
As it has been mentioned above, one of the main challenges for the harmonious development of the renewable hydrogen sector in the EU, including utilization of existing gas infrastructure, is a lack of a single standardization framework. However, the European Clean Hydrogen Alliance's *European Clean Hydrogen Alliance Roadmap on Standardization* provides a

comprehensive overview of the challenges and needs of standardization identified by members of the Alliance. The lack of uniform standards remains a major obstacle to the faster development of hydrogen technologies and to the attraction of investment at different stages of the hydrogen energy value chain. The roadmap covers all standardization needs of the hydrogen value chain, from production, distribution, transport and storage to final consumption in different economic sectors [19].

3. NATURAL GAS/BIOMETHANE AND HYDROGEN BLENDING AND ITS CHALLENGES

Over the past decade, several visions have been presented on possible transformation of the European gas supply network for transportation of 100 % hydrogen. For example, the EHB report states that five pan-European hydrogen supply and import corridors could emerge by 2030, connecting industrial clusters, ports and hydrogen valleys to key local and global hydrogen production and logistics centres. European hydrogen network could grow to more than 50 000 km by 2040, mainly by using existing natural gas infrastructure [20].

There are two options for transporting hydrogen through existing natural gas pipelines: as a blend with other gases (natural gas, biomethane, etc.) or as pure hydrogen, in both cases equipment is required to feed hydrogen into the gas network. The first option requires the addition of a certain amount of hydrogen to a gas pipeline that already transports natural gas or blends of natural gas/biomethane, producing a blend of hydrogen/natural gas/biomethane with a certain percentage of hydrogen in it. In the latter case, the complete replacement of natural gas or natural gas/biomethane blend with hydrogen as a new transport fuel is necessary [21]. Figure 3 shows the principal technical scheme for injection of hydrogen into the gas network and Fig. 4 outlines the same process with regulatory applications and major stages in hydrogen blending with natural gas/biomethane and delivery to end-users.



1. Gas supply station
2. Gas distribution or transmission system
3. Measurement and control point — pressure control/flow control/measurement etc.
4. Hydrogen pipeline (gas blend pipeline)
5. Production of hydrogen gas
6. Gas composition/flow information
7. Gas supply for forming a gas blend

Fig. 3. Principal technical scheme for injection of hydrogen into the existing gas network.

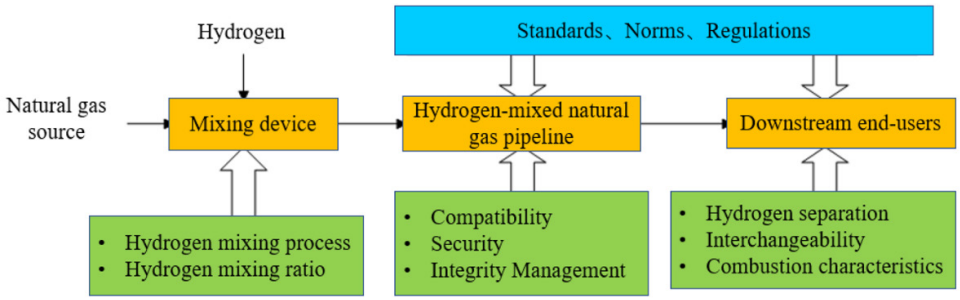


Fig. 4. Regulatory applications and major stages in hydrogen blending with natural gas/biomethane and delivery to end-users.

Also, the system for introducing hydrogen into an existing gas supply network or autonomous hydrogen network shall cover a wide range of measures, including pressure regulation, protection against overpressure, testing to ensure gas quality as required, gas measurement and, if necessary, odorization.

Numerous studies concerning the use of natural gas/biomethane and hydrogen blends have only taken into account the impact of hydrogen in the final consumption sector, in particular its combustion problems, by examining, for example, the impact of hydrogen on burner performance and the combustion process itself (capacity, efficiency, emissions, etc.). However, in order to test the readiness of the gas infrastructure for the new fuel and make the necessary adjustments, in-depth, comprehensive studies are needed on the impact of hydrogen on the materials that make up all network components and equipment. Such studies are particularly important for the transmission network, which consists of large diameter pipelines, and connects gas system entry points with many long-distance final consumers. The transmission system operates under high pressure conditions (≥ 50 ba), making possible hydrogen leaks potentially more dangerous than they would be in the distribution system [22].

The main risk factors associated with growing concentration of hydrogen in natural gas/biomethane and hydrogen blends are: leaks, as hydrogen can diffuse through many materials considered impermeable to other gases, buoyancy as hydrogen rises quickly under atmospheric conditions, flammability when mixed with air, – can easily ignite or/and explode, hydrogen-induced cracking as reduction in the ductility of a metal can occur due to absorbed hydrogen (steels, iron, nickel, titanium, cobalt, and their alloys) [23]. Also, hydrogen energy content is about one-third of the natural gas. Thus, not only more hydrogen-blended natural gas is needed to deliver the same amount of energy to users compared to pure natural gas but also a higher volumetric flow rate is required. Options for the latter include increasing operating pressure in a distribution system or replacing the existing pipelines with ones of larger diameter [24].

As it has been mentioned above, most metals from which existing gas transmission pipelines are made suffer from hydrogen-induced cracking, especially at high pressure. This may result in necessity to introduce more strict requirements in production of such pipelines, if they are not totally replaced with polyethylene analogues. Specially designed pipelines for the transmission of hydrogen may significantly increase construction costs per kilometer of the hydrogen transmission network in comparison with pipelines for transportation of

natural gas/biomethane [25].

Metal fragility caused by hydrogen is one of the main challenges for the wider use of hydrogen in the existing EU gas transmission network, where steel gas pipelines currently dominate. The risk of fragility depends heavily on the quality of the steel, in particular its microstructure, as well as the conditions under which the material has been exposed over a long period of time [26]. The literature explores the impact of metal fragility caused by hydrogen on carbon steels with quality up to API 5L X80 to determine the relationship between hydrogen concentration in the gas blend and the failure load of the gas pipeline [27].

Another important aspect of ensuring the safe and efficient use of gas pipelines is the prevention of critical gas leaks in valves and other elements of infrastructure. It is therefore essential to implement regular maintenance and inspection measures in a whole gas network, not only pipelines. Hydrogen is believed to leak at the same rate as natural gas in low and medium pressure systems (natural gas distribution system and autonomous, local natural gas supply systems), but as the system operating pressure increases, the leakage rate increases, too. Some studies have also attempted to predict potential leakage spots by highlighting cell connection sites as some of the most critical points [28].

A blend of natural gas/biomethane and hydrogen can potentially cause problems not only for the integrity of the pipelines but also for the safe use of other elements of the gas supply system, so system security requires much greater attention than in the case of separate transmission and distribution of natural gas/biomethane. A number of significant indicators for natural gas/biomethane and hydrogen are also different, such as the Wobbe Index, which may directly affect the accounting of the blend (accuracy of gas meters [29]) and burners used in gas heating appliances or industrial natural gas combustion systems. Furthermore, hydrogen has a lower calorific value than natural gas, thus blending hydrogen with natural gas will reduce the calorific value of a blend [30]. The change in the Wobbe Index and calorific value of the blend of natural gas/biomethane and hydrogen under the conditions of the different percentage of hydrogen in the gas blend is shown in Fig. 5.

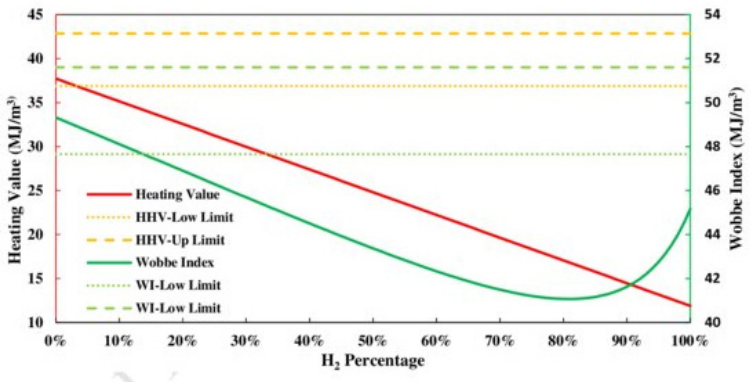


Fig. 5. The change in the Wobbe Index and calorific (heating) value of the blend of natural gas/biomethane and hydrogen [31].

4. DEBLENDING SOLUTIONS

Several technical solutions for the simultaneous transmission and distribution of hydrogen and natural gas/biomethane are currently offered on the European and global markets, including blending facilities of natural gas/biomethane and hydrogen, where the percentage of hydrogen in a gas blend can vary significantly. Such solutions are offered by manufacturers and suppliers such as "JLS International", "Emersons" [28], "Linde" and "Honeywell". Both stationary gas blending solutions and equipment with moving elements are available. Basically, both solutions are currently being offered for large diameter pipelines.

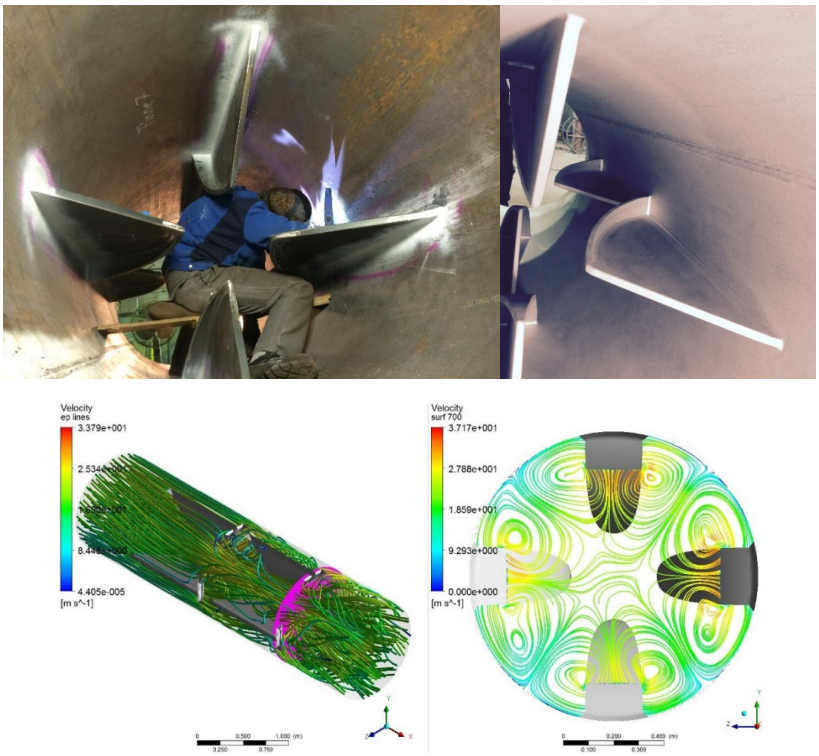


Fig. 6. Stationary, pipe-mounted, gas mixer assembly (upper images), gas mixer performance test (computer simulation) in different gas blending modes [32].

Stationary solutions are used not only for blending of natural gas/biomethane and hydrogen, but also for the addition of odorant or biomethane to natural gas. For example, "Emersons" and "Linde" offer integrated natural gas/biomethane and hydrogen blending solutions suitable for lower pressure regimes and smaller pipe diameters and, in particular, for the gas distribution network [33], [34]. The bulk of the gas distribution network today consists of polyethylene pipes, the use and maintenance of which are less complex than in the case of steel pipelines. Polyethylene pipelines have properties such as corrosion resistance, high elasticity and excellent low temperature toleration properties, which also make them more resilient to potential negative effects of hydrogen [35].



Fig. 7. "Emerson" *El Campo* natural gas/biomethane and hydrogen blending test facility.

Although the principles of blending natural gas/biomethane and hydrogen are similar to both small and large industrial solutions, some producers, such as "Honeywell", work at development of complex gas/biomethane to hydrogen grid solutions, where different scale applications coexist.

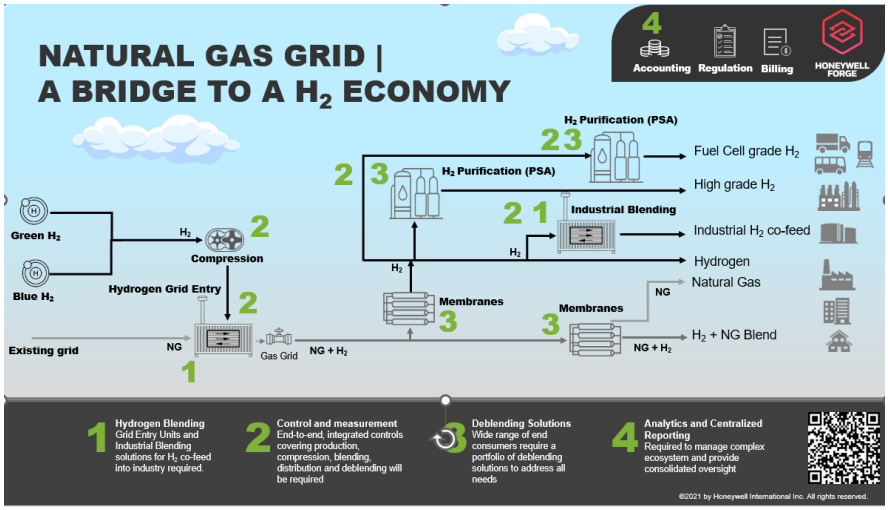


Fig. 8. "Honeywell" complex gas/biomethane to hydrogen grid solutions [34].

However, as the main function of the gas network is to supply gas resources to final customers, it may also be necessary to develop a universal natural gas/biomethane and hydrogen blend separation or deblending technology in the future. This will be necessary if certain categories of gas end-users connected to existing diversified gas supply networks could not, for objective reasons, receive and use a blend of natural gas/biomethane and hydrogen [36]. Currently, the hydrogen separation technology used is made almost exclusively for a high hydrogen concentration gas blend, and there is still room for research in sector of gas deblending with relatively low hydrogen content ($\leq 5 - 30$ %). Pressure oscillation adsorption and fractionated/cryogenic distillation systems are available on the market, but they are generally not cost-effective because they are energy-intensive, especially when the hydrogen content of the gas

blend is low. For this reason, membrane-based technologies are considered to be more prospective for ensuring high purity hydrogen flow in the future [37], [38].

5. CONCLUSIONS

Blending and transportation of hydrogen in existing gas networks are the most topical issues in decarbonization and diversification of the gas transportation infrastructure in the EU. At the moment, a few obstacles exist in terms of wider hydrogen application in the area, namely:

- a lack of harmonized, EU-wide regulatory framework governing natural gas/biomethane and hydrogen blending;
- different percentage of hydrogen acceptable for transportation and distribution in existing gas networks, which can vary significantly from country to country (from 0 up to 12%);
- existence of limitations preventing hydrogen bending with methane-based gaseous fuels, if there are possibilities for these bends be transported and traded abroad;
- existence of limitations preventing hydrogen bending with methane-based gaseous fuels, if there are possibilities for these bends to reach certain UGS facilities;
- limited possibility to use higher hydrogen percentage in natural gas/biomethane and hydrogen blends in the whole national gas transportation and distribution network (access only to local or autonomous sections of gas distribution networks);
- a necessity to develop a universal natural gas/biomethane and hydrogen blend separation or deblending technology/set of technologies suitable to certain categories of gas end-users connected to existing diversified gas supply networks, who, for objective reasons, cannot receive and use a blend of natural gas/biomethane and hydrogen.

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