» HOW TO TRANSPORT AND STORE HYDROGEN – FACTS AND FIGURES

ENTSOG, GIE and Hydrogen Europe have joined forces on a paper that answers a number of fundamental questions about gaseous and liquid hydrogen transport and storage. This paper provides an objective and informative analysis on key concepts, terminology and facts and figures from different public sources.

entsog // Gas Infrastructure Europe // Hydrogen Europe

CONTENT

1 » WHAT ARE THE PATHWAYS THAT ALLOW FOR THE INTEGRATION OF HYDROGEN IN THE EXISTING GAS INFRASTRUCTURE AND MARKET?

There are three pathways for the integration of hydrogen into the gas system: the injection of hydrogen and its blending with natural gas in the existing gas infrastructure, the development of a dedicated hydrogen network through conversion of the existing gas infrastructure or via the construction of new hydrogen infrastructure and finally via methanation, consisting in capturing CO_2, combined with hydrogen in order to produce e-methane, injected in the gas network. Those models are complementary and depend on the production technology, the concerned zone or even the temporality of the projects.

Today the gas infrastructure can accommodate any form of low carbon hydrogen, independently from the technology used for its production, such as electrolysis, gasification of biomass, steam methane reforming combined with capture of CO_2 or steam methane reforming of biomethane, electrolysis of molten salt.

2 » WHAT IS HYDROGEN BLENDING?

Hydrogen blending is the injection in the existing gas infrastructure of a share of hydrogen into the overall volume of gaseous energy carriers. With exceptions related to injected shares and areas of application, the respective hydrogen blending levels may not substantially affect the capacity of the gas infrastructure[1].

3 » WHAT IS HYDROGEN DEBLENDING?

Hydrogen deblending is the reverse process of hydrogen blending and allows to extract pure hydrogen for dedicated uses (e.g. hydrogen fuel cells, feedstock) as well as reasonably hydrogen-free natural gas. For hydrogen deblending, different designs of membrane plants and combinations with other technologies are used (e.g. polymer membrane, carbon membrane, metal membranes, glass/ceramic membranes, membrane-PSA) to separate hydrogen from gaseous energy carriers. There are several important factors to be considered when choosing the most suitable technology, such as permeability, selectivity, stability of the membrane material, effects of discontinuous operation on the operation, design of the membrane plant, effects of different hydrogen concentration on the separation process. Hydrogen separation effectiveness depends on the hydrogen concentration in methane. It is also important to ensure proper management of the separated hydrogen. However, the technology is currently under development and additional R&D analysis is needed.

4 » HOW MUCH HYDROGEN CAN BE BLENDED INTO THE EXISTING GAS PIPELINES?

The maximum allowable hydrogen concentration depends mainly on pressure fluctuations, structure and existing defects. However, widespread knowledge to date indicates that, for some grid sections, certain blending percentages (e.g. 2 % – 10 % in volumetric terms) are technically feasible with few adaptations in some Member States. Although additional tests are needed some operators consider 20 % the upper bound due in particular to the requirements for downstream users to be adapted beyond this point[2] (Figure 1). As regards to technical regulation, blending of hydrogen is explicitly recognized by a few Member States.

1 Hydrogen Europe Response to Energy System Integration public consultation.

2 GRTgaz et al. Technical and economic conditions for injecting hydrogen into natural gas networks, and Gas for Climate 'European Hydrogen Backbone' July 2020

OVERVIEW OF AVAILABLE TEST RESULTS* AND REGULATORY LIMITS FOR HYDROGEN ADMISSION INTO THE EXISTING NATURAL GAS INFRASTRUCTURE AND END USE

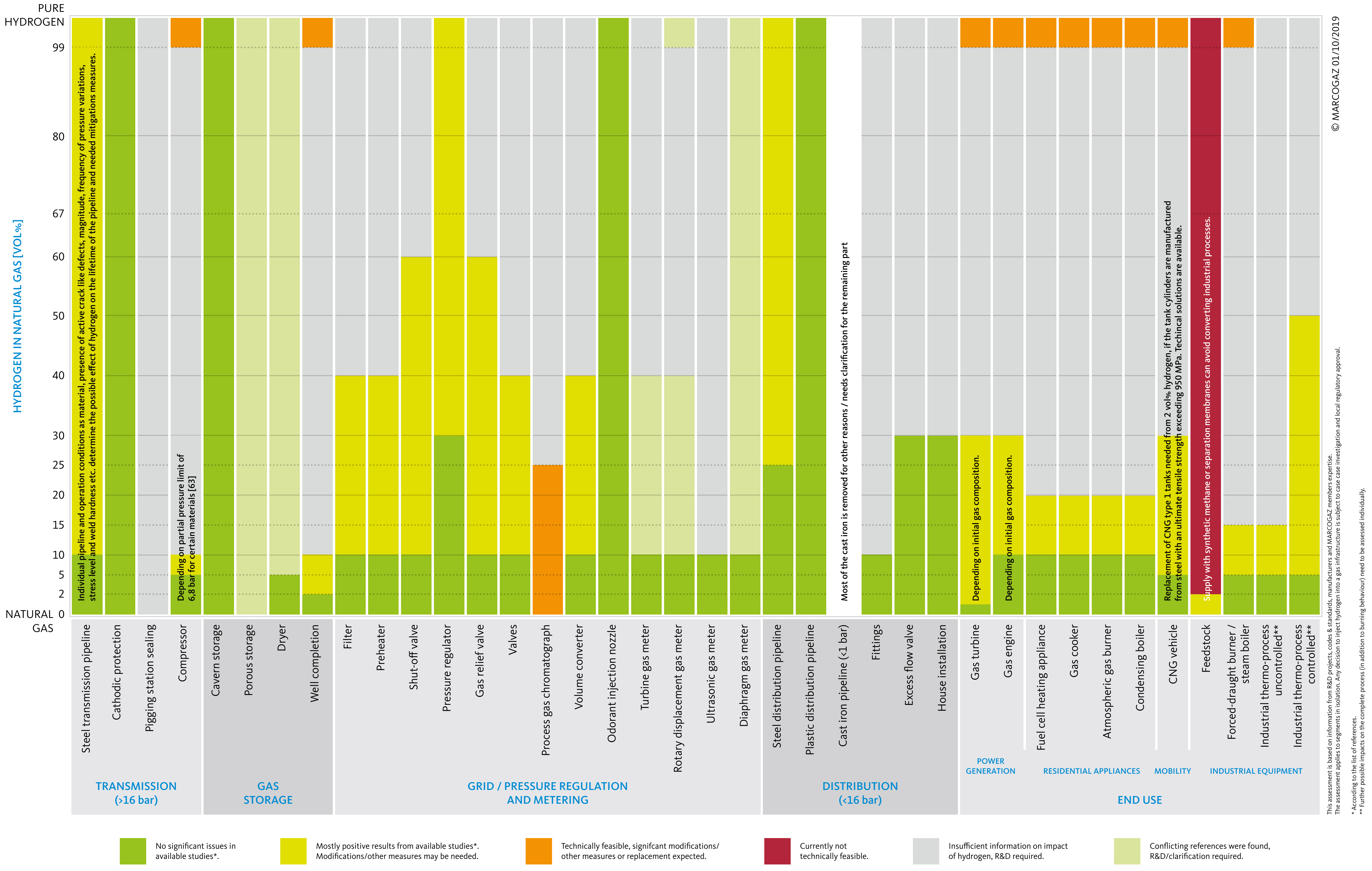


Figure 1 » Overview of available test results and regulatory limits for hydrogen admission into the existing natural gas infrastructure and end use (by marcogaz).
(The infographic is not representing the whole system. Data from each system operators shall be treated as the best source of information on the limits of hydrogen admission.)

5 » WHAT ARE THE ADVANTAGES OF HYDROGEN BLENDING?

» Blending represents an easy entry point into the hydrogen economy, allowing for quick decentralised deployment of renewable and low-carbon hydrogen technologies as well as centralised production scale-up. Hydrogen blending can reduce greenhouse gas emissions (GHG) when produced from clean energy sources[3]. Additional separation steps might be necessary if pure hydrogen or methane is needed.

» Blending can also be a cost-effective transitional option in those regions without parallel or duplicated networks, or without (potentially) available gas infrastructure capacity which can be easily repurposed to hydrogen in the short-term.

6 » WHO ARE THE CUSTOMERS OF BLENDED H_2/NATURAL GAS ADMIXTURES?

Consumers of hydrogen admixtures are the same consumers connected today to networks compatible with natural gas, such as industries and users of domestic gas heating. In some concrete cases, however, some end-users do not tolerate admixtures over certain concentration levels and hence, gas quality handling technologies would be needed.

7 » WHAT ARE THE LIMITATIONS ON HYDROGEN BLENDING INTO THE EXISTING GAS PIPELINES?

Main challenges can include measurement, energy conversion, process gas chromatographs, and gas metering. Moreover, there are different levels of blending shares across the EU, posing an obstacle to the interoperability of gas networks. Along a pipeline, friction causes transported gas to lose pressure. Compressor stations compensate these losses to boost the system's energy throughput. Hydrogen has a significantly lower molar weight than natural gas, which is a parameter for the commonly used centrifugal compressors. Therefore, existing compressors are usually not fully optimised for blends, although different compressors models react in different ways to hydrogen blends. For example, SIEMENS states that, when transported, a hydrogen share below 10 % only leads to minor changes of existing compressors, while a share of above 40 % requires its replacement.[4] Compressors themselves are usually driven by gas turbines. Many new and recently installed gas turbines show strong resilience towards blends[5]. Some gas turbines would however require modifications, and equipment manufacturers are working to offer adequate solutions in the short term. Besides, valves and connected underground storages (UGS) must accept respective hydrogen levels. While salt cavern storages' adaptability is promising, more research is necessary for UGSs that store gas in porous rock (see questions 25–31).[6] In general, possible effects of hydrogen on all relevant materials needs to be assessed.

3 NREL: Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues, 2013

4 Siemens Energy, Nowega, GASCADE: Whitepaper: Hydrogen infrastructure – the pillar of energy transition – The practical conversion of long-distance gas network to hydrogen operation, 2020

5 Siemens Energy Global (siemens-energy.com): Hydrogen capable gas turbine, 2019

6 Marewski, Engel, Steiner: Conversion of existing natural gas pipelines to transport hydrogen, in Pipelinetechnik 02/2020

8 » WHAT IS HYDROGEN EMBRITTLEMENT?

Hydrogen embrittlement is a metal's loss of ductility and reduction of load bearing capability due to the absorption of hydrogen atoms or molecules by the metal. The result of hydrogen embrittlement is that components crack and fracture at stresses less than the yield strength of the metal[7]. Solutions include lowering piping design factor, identification of piping hydrogen toughness, the application of 'inner coating' to chemically protect the steel wall, monitoring of pipes, development of integrity plans and safety coefficients or changes in the transmission conditions. The optimal solution varies per pipeline, as it depends on several criteria including pipeline transport capacity requirements, status of existing pipelines and trade-offs between capital and operating expenditure[8]. Carbon steel (metallic) pipelines transporting 100 % H_2 have been operating for many years[9].

9 » WHAT IS THE DIFFERENCE BETWEEN RETROFITTING AND REPURPOSING EXISTING GAS INFRASTRUCTURE FOR HYDROGEN?

Retrofitting is an upgrade of existing infrastructure that allows the injection of certain amounts of hydrogen into a natural gas stream up to a technically-sound threshold of H_2/CH_4 mixture (i.e. blending). Repurposing implies converting an existing natural gas pipeline into a dedicated hydrogen pipeline.

10 » WHAT ARE THE COSTS OF REPURPOSING THE EXISTING NATURAL GAS INFRASTRUCTURE FOR 100 % HYDROGEN TRANSPORT?

According to some evaluations on this topic, repurposing costs of typical transmission pipelines are expected to be between 0.2 and 0.6 Million € per kilometer[10 11 12]. However, the European Hydrogen Backbone report published in July 2020 underlines that "repurposing the existing gas infrastructure is possible at 10–35 % of the costs that would be required for a newly built hydrogen pipeline"[13]. The updated European Hydrogen Backbone report[14] found that the costs of hydrogen transport will probably be between 0.11 and 0.21 €/kgH_2/1,000 km based on the following expenditures to build a European hydrogen backbone including compressor stations:

- » CAPEX: 43 to 81 billion € (building and repurposing)
- » OPEX: 1.7 to 3.8 billion €/year

7 Hydrogen Embrittlement of Steel - Industrial Metallurgists

8 Gas for Climate, Extending the European Hydrogen Backbone, April 2021

9 Questions and Issues on Hydrogen Pipelines, August 2015

10 European Commission: Hydrogen generation in Europe: Overview of costs and key benefits, July 2020

11 Hydrogen Europe: Green Hydrogen Investment and Support Report, 2020

12 German TSOs, Draft: German National Network Development Plan 2020–2030

13 Gas for Climate: European Hydrogen Backbone, July 2020

14 Gas for Climate: Extending the European Hydrogen Backbone, April 2021

11 » WHAT ARE THE TECHNICAL CONSIDERATIONS RELATED TO REPURPOSING AN EXISTING NATURAL GAS INFRASTRUCTURE TO HYDROGEN INFRASTRUCTURE?

The repurposing of an existing natural gas infrastructure to hydrogen implies dealing with several technical challenges linked to the different chemical properties of hydrogen in comparison to natural gas. In general terms, the technical state and chemical composition of infrastructure materials need to be considered when assessing if existing pipelines can transport 100 % hydrogen. According to Gas for Climate, existing natural gas infrastructure does not require massive changes to be fit for 100 % hydrogen transport as the infrastructure materials are often fit for hydrogen transport as well[15]. However, the decision whether existing pipeline can transport 100 % hydrogen and the respective changes need to be considered case by case taking into account the technical state and chemical composition of the material.

At standard conditions, methane has three times the calorific heating value per cubic meter of hydrogen. Assuming the same operating pressure[16] and the same pressure drop along the pipeline, hydrogen will also flow at three times the velocity due to its low density. Further the same gas pipeline today transporting mainly natural gas, can transport about three times as many cubic meters of hydrogen during a given period and thus deliver roughly the same amount of energy. This results in the energy transportation capacity being only slightly smaller compared to high-calorific natural gas.

The main elements of the conversion process include:

» **Technical conditions of gas pipeline**;

» **Cleaning**;

» **Integrity management of the steel pipes and fittings:** As for natural gas pipelines, it is necessary to regularly inspect the pipeline and identify possible cracks.[17] Embrittlement can in principle accelerate propagation of cracks . This is only likely, though, if the pipeline already has fractures and is subjected to dynamic stresses due to fluctuating internal pressure during hydrogen operation. It is therefore necessary to constantly monitor crack growth based on the pressure fluctuations measurements already done for operational purposes. The replacement of valves could be required.

» **Compression of hydrogen:** a complete switch to a 100 % hydrogen pipeline requires installing new turbines or motors and new compressors. Analyses by some gas TSOs show that operating hydrogen pipelines at less than their maximum capacity gives much more attractive transport costs per MWh transported as additional expensive high-capacity compressor stations and corresponding energy consumption can be avoided. The fixed pipeline-related costs per MWh obviously increase, yet compressor costs and the corresponding cost of the energy fall sharply.[18]

» **Tightness of the system including valves:** as hydrogen is much smaller molecule than methane internal and external tightness of the system needs to be adequately certified, additionally material used for sealing needs to be chosen as applicable to work with hydrogen.

» **Replacement of measuring equipment:** gas chromatographs has to be equipped with an additional column able to measure hydrogen, i.e. in case of pressure transducers dedicated membranes able to cope with hydrogen needs to be used, gas meters needs to be ready to properly operate with hydrogen.

» **Upgrade of the software:** software of the flow computers needs to be upgraded, i.e. calculation algorithms have to include hydrogen.

15 Gas for Climate: European Hydrogen Backbone, July 2020

16 This is only possible if pressure is the same for natural gas and H_2, which is not completely clear today due to embrittlement issues.

17 Siemens Energy: What's your purpose? Reusing gas infrastructure for hydrogen transportation, September 2020

18 Gas for Climate: European Hydrogen Backbone, July 2020

12 » WHAT ARE THE COSTS OF REPURPOSING THE EXISTING GAS PIPELINES VS. BUILDING NEW DEDICATED H_2 PIPELINES?

The average repurposing costs of transmission pipelines are expected to be between 10 and 35 % of the construction costs for new dedicated hydrogen pipelines. Those values are provided by the European Hydrogen Backbone report, while cost assumptions from other sources like the German national network development plan remain within those boundaries.[19 20 21 22]

13 » WHAT OTHER OPTIONS ARE AVAILABLE TO TRANSPORT HYDROGEN BESIDES PIPELINES?

Apart from the transport via pipelines, hydrogen can be also transported via:

» **Marine terminals:** hydrogen can be exported and imported via sea-side terminals including adapted LNG terminals, which have been prepared for that task. In providing maritime logistics, storage, conversion, pipeline connections, multimodal transport connections and quality management, those terminals can be multipurpose, multi-energy carrier entry gates to the EU (see question 23).

» **Hydrogen shipping:** it involves the transportation of hydrogen over large distances by ship in gaseous or liquid form, or via liquid or gaseous hydrogen carriers.

» **Hydrogen truckloading:** it refers to the transportation of hydrogen by truck in gaseous or liquefied form, or via liquid or gaseous hydrogen carriers.

» **Hydrogen transportation by rail:** hydrogen can be carried out:
- **in gaseous form or via gaseous hydrogen carriers** using compressed gas cylinders via tube trailers.
- **as a liquid in specialized containers** for transporting hydrogen in liquid form or via liquid hydrogen carriers.

19 Gas for Climate: European Hydrogen Backbone, July 2020

20 European Commission: Hydrogen generation in Europe: Overview of costs and key benefits, July 2020

21 Hydrogen Europe: Green Hydrogen Investment and Support Report, 2020

22 German TSOs, Draft: German National Network Development Plan 2020–2030

In order to transport and distribute hydrogen different technologies are possible. These technologies not only allow for the transport of hydrogen, but also for its storage:

- **Liquid organic hydrogen carriers (LOHC):** it is a technology which enables a safe and effective high-density hydrogen storage in an easy-to-handle organic liquid, thus reducing the need for pressurized tanks for storage and transport.
- **Liquefied hydrogen (LH_2):** hydrogen liquefies at −253°C. Liquefaction increases the density of hydrogen by a factor of around 800, and the storage volume falls correspondingly[23]. Once liquefied, it can be maintained as a liquid in pressurized and thermally insulated containers. However, experience with LH_2 in a distributed energy system is lacking.
- **Pressurised hydrogen:** hydrogen can be pressurised to be stored and transported; this pressurisation can be applied to pure hydrogen or to hydrogen mixtures with other gases.
- **Synthetic gas:** hydrogen can be combined with CO_2 through a chemical reaction and transformed into methane. This results in synthetic gas (which is mainly methane, the main component of natural gas) and it can easily be transported and stored within the existing gas infrastructure with no modification.
- **Ammonia:** by combining hydrogen with nitrogen to produce ammonia, it allows for the transport and storage of energy in liquid state (liquefaction at around −30°C).
- **Methanol:** by combining hydrogen with CO_2 to produce methanol, it allows for the transport and storage of energy in liquid state.

The competitiveness of the different options will depend on the distance over which hydrogen is transported, and on scale and end use. If hydrogen needs to be shipped overseas, it generally has to be liquefied or transported as ammonia or in LOHCs. For distances below 1,500 km, transporting hydrogen as a gas by pipeline is generally the cheapest delivery option; above 1,500 km, shipping hydrogen as ammonia or an LOHC may be more cost-effective[24]. Conversion costs can significantly impact business cases since as much 28 % (11 kWh/kg) of the transported energy can be consumed during LOHC dehydration[25]. Since this step requires high temperatures, LOHC transport to places where waste heat sources already exist may prove advantageous.

14 » WHY IS THERE A NEED FOR MARINE AND PORT INFRASTRUCTURE AND TERMINALS BESIDES PIPELINES?

Studies predict significant imbalances in clean hydrogen supply and demand. For instance, the Port of Rotterdam estimates that, by 2050, 20 million tons of hydrogen will be transported through the port to meet demand in Northwest Europe[26]. Marine terminals, with multimodal transportation connections, conversion and other facilities will be key to connect centres of production and demand in Europe and beyond, contributing to the EU's security of supply.

23 Shell Hydrogen Study: Energy of the Future?, 2017

24 International Energy Agency: The future of hydrogen – Seizing today's opportunities

25 Hydrogenious LOHC Technologies GmbH

26 Port of Rotterdam: Port of Rotterdam becomes international hydrogen hub, May 2020

15 » WHAT IS THE COST OF TRANSPORTING HYDROGEN VIA PIPELINES?

The costs mainly depend on the investments in pipelines and compressor stations as well as operating expenditures which include energy for compression. Required compression energy and specific costs, however, strongly depend on the real usage of the system. Depending on the scenario, a European hydrogen backbone system is expected to show levelized costs of 2.3 to 4.4 € for the transport of 1 MWh over 1,000 km. This would add less than 10 % to the production costs of renewable or low-carbon hydrogen.[27]

16 » DO WE NEED MEDIUM-LONG DISTANCE TRANSPORTATION INFRASTRUCTURE TO TRANSPORT HYDROGEN?

The European Commission's Hydrogen Strategy (July 2020) states that a pan-European hydrogen grid will need to be planned for the transport of hydrogen across the EU. Moreover, the same Strategy acknowledges that international hydrogen trade can also develop, in particular with the EU's neighbouring countries in Eastern Europe and in the Southern and Eastern Mediterranean countries. Global hydrogen trade is expected to develop over time. The development of renewable electricity from solar and wind has been creating a geographical separation between the renewable electricity production (e.g. offshore or coastal wind parks in the North, photovoltaic plants in the South) and energy consumption in major industrial centres of the continent. In a sustainable energy system, where the need for gaseous energy will still be consistent not only to serve industrial processes, but also to bridge the mismatch in time between renewable electricity supply and demand, it will be crucial to make available all possible locations for hydrogen production sites, store strategically and ensure that stored quantities reach customers where and when the energy is needed.

17 » WHAT IS A EUROPEAN HYDROGEN BACKBONE?

The European Hydrogen Backbone (EHB[28]) is a vision of 11 gas TSOs from 10 European countries on the future role of the gas infrastructure. The group of gas TSOs is growing and gathers today 23 European gas infrastructure companies. By 2040, the proposed backbone can have a total length of 39,700 km, consisting of approximately 69 % retrofitted existing infrastructure and 31 % of new hydrogen pipelines.

The concept of a European hydrogen backbone is a different one and refers to a high-pressure pipeline core infrastructure network that efficiently connects hydrogen supply sources and major consumers across Europe. It will initially connect industrial clusters to enhance security of supply and facilitate hydrogen markets. Subsequently, it will allow the increasing renewable electricity generation (which can be converted to hydrogen via electrolysis) to be first of all connected to remote and hard-to-abate consumers in Europe's industrial centres. It provides large-scale storage solutions while easing the strain on the electricity transmission infrastructure. It also provides for international connections to global production areas. By using repurposed natural gas pipelines as the backbone's core corridors, the technical implementation can take place at reasonable cost, duration, and risk.

27 Gas for Climate: European Hydrogen Backbone, July 2020

28 European Hydrogen Backbone website

18 » WHAT IS A HYDROGEN VALLEY?

A Hydrogen Valley is an initiative that aims to promote the emergence and implementation of hydrogen projects across the whole value chain (from upstream to mid- and downstream) generally at a local or regional scale. Concretely, hydrogen projects under a Hydrogen Valley can cover not only the production of hydrogen via electrolysis or other low carbon technologies such as CCS but also its transport and storage as well as the development of end-uses in mobility and industry for instance. There are currently 32 Hydrogen Valleys across 18 countries, representing a total investment of over €30 billion. 21 Valleys are located in Europe. Most of them are small-scale initiatives (‹ € 100 million of total investment) and the other half is split between middle- (€ 100 – € 1,000 million) and large scale (› € 1,000 million) projects. More information can be found on the Mission Innovation Hydrogen Valley Platform developed by the FCH 2 JU.

19 » WHAT IS THE ROLE OF HYDROGEN INFRASTRUCTURE IN DEPLOYING OFFSHORE WIND?

Hydrogen provides a solution to make up for the intermittency of wind power production by allowing the storage of energy, possibly in large quantities and over large periods of time. Offshore wind plants are subject to a specific environmental context since they are located at sea and thereby have less access to the traditional electricity grid. Several models can be considered for hydrogen to connect power generated from offshore to energy demand hubs onshore:

» the 'on-site' model gathers both renewable electricity generation and electrolysis at the same geographical location, with the possible import of grid electricity implying the need for Guarantees of Origin.

» the 'upstream' model is a variation in which no grid power import is foreseen and, therefore, requires the electrolyser to be connected at proximity of high-capacity offshore energy plant(s) to ensure a sufficient load factor.

Whereas some level of power grid extension may be needed to cope with the expansion of renewables, the conversion of wind power into hydrogen and its transport to shore via a hydrogen grid allows to considerably reduce infrastructure costs. Besides, the energy content is substantially higher when energy is carried via gas pipelines compared to a high-voltage direct-current (HVDC) power line. All in all, for the same investment a hydrogen pipe can transport 10–20 times more energy than an electricity cable.[29]

In its Offshore Renewable Strategy, the Commission notes that 'on-site conversion of renewable electricity into hydrogen and its shipping or on-site fuelling will become relevant.' The maritime sector will indeed be a major enabling partner to materialise those synergies between offshore renewables and hydrogen. Namely, hydrogen produced offshore could be transported by ships or hydrogen pipelines to demand hubs such as ports. Hydrogen-fuelled ships can bring crew to offshore platforms and wind turbines (for maintenance). The synergies between offshore energy and hydrogen thereby offer much potential, not least in terms of circularity in the value chains, where clean steel produced with hydrogen can be used to build the wind turbines whose power will feed into the electrolyser producing the hydrogen, itself feeding clean steel factories and hydrogen-powered ships for both hydrogen transport and offshore wind plants maintenance.

29 Strategic Analysis: Analysis of Advanced H_2 Production & Delivery Pathways, June 2018

20 » WHAT IS THE QUALITY SPECIFICATION FOR HYDROGEN TRANSPORTATION VIA DEDICATED HYDROGEN PIPELINES?

There are currently no EU-wide technical specifications related to the quality of hydrogen transported via dedicated hydrogen pipelines in gaseous form. The absence of a harmonised EU regulation could lead to a fragmentation of the hydrogen market and may create problems at cross-border connection points. Admissible ranges of purity and impurities should be defined at appropriate levels not undermining hydrogen developments, and hydrogen quality standards should be developed and adopted at EU level.

Both a draft EASEE-gas CBP and a German standard look into required purities for hydrogen transport via repurposed natural gas pipelines[30] Also CEN is studying to launch the standardisation process for a European standard[31]. It should be noted that certain industries require different on-site purity levels[32].

21 » HOW CAN LNG TERMINALS BE USED FOR IMPORTING AND STORING HYDROGEN?

LNG terminals offer great advantages for becoming entry gates of hydrogen into the EU. Located on the seaside, LNG terminals provide industrial-scale access to maritime logistics, have tanks with large storage capacities, and direct connection to the gas grid. LNG terminals are ready to work in cryogenic conditions, and operators have profound experience in management of conversion and gas quality activities.

After an adaptation process, LNG terminals can be ready to import and store hydrogen in various forms. GIE has identified a number of pathways[33] including liquefied hydrogen, LOHC, or other chemical carriers built with hydrogen (e. g. methanol, ammonia, etc.). To enable these possibilities regulatory and policy support is needed upstream production and coordination across the whole value chain.

22 » HOW CAN LNG TERMINALS BE REPURPOSED WHEN METHANE LIQUEFIES AT –160° C AND HYDROGEN AT –253° C?

Most of the process technology and safety principles that relate to LNG will relate to hydrogen, and while there are different factors involved, in the end the risk level is not expected to be completely different. While broad design principles might look similar, the components, like valves, piping, etc., are not necessarily interchangeable. Therefore, it will be necessary to replace them, and this implies a higher cost. However, while it may be a novel application to repurpose an LNG terminal into a LH_2 terminal, the technology itself is not new. The equipment and expertise have been in existence for a long time. In different parts of the world, LH_2 production, handling, and distribution have been performed for over 50 years, and the experience of the LNG industry will be invaluable to build on that existing knowledge. However, a risk assessment of LNG terminals would need to be carried out in order to analyse the impact on the process conditions, properties of mixtures and consequences of the different scenarios, considering LH_2 instead of LNG.

30 Draft DVGW-Code of Practice G260 (Arbeitsblatt G260 E Entwurf 2020-09)

31 New work item proposal 'Hydrogen in converted gas systems' for CEN/TC 234 / WG11.

32 Purity specifications for fuel cells are set by ISO-14687, SAE-2719 and CEN-17124.

33 GIE, Frontier Economics on The role of LNG in the energy sector transition – regulatory recommendations and DNV GL study on the import of liquid renewable energy – technology cost assessment

23 » ARE ALL KINDS OF GAS STORAGE FACILITIES (DEPLETED FIELDS, AQUIFERS, SALT CAVERNS) ABLE TO STORE HYDROGEN? UP TO WHICH DENSITY?

In Europe, three types of underground formations can provide large-scale cyclical and seasonal storage of hydrogen to secure its supply, allow electrolysers to operate flexibly and assist electricity to cover peak demand: salt caverns, aquifers and depleted fields. Salt caverns are suitable for storing pure hydrogen due to their low cushion gas requirement, the large sealing capacity of rock salt and the inert nature of salt structures, limiting the contamination of the hydrogen stored[34]. This technology has already been used for many decades in Great Britain and the United States, with volumes varying from 210,000 m³ to 580,000 m³, confirming unequivocally the technical feasibility of this option. Regarding storage in porous rock – aquifers and depleted reservoirs –, the dissolution and transportation of hydrogen in water, its fingering[35] and confinement in storage are well known and similar to natural gas. Besides, current research to identify potential chemical or biological reactions in solutions in these reservoirs is ongoing and showing fair potential. Underground hydrogen storage will thus complement linepack flexibility provided by hydrogen pipelines and on-site storage at import terminals.

24 » HOW CAN LARGE-SCALE SEASONAL AND CYCLICAL STORAGE OF HYDROGEN HELP DEPLOY RENEWABLE ENERGY?

With higher electrification rates and increasing deployment of renewable energy, large-scale storages will be essential to manage system balancing on short-term and seasonal timescales. In the coming decades, the electricity network will cope with much larger seasonal peaks and daily fluctuations in demand and supply. To address this issue and prevent blackouts caused by an overload, renewable electricity will need to be complemented with dispatchable energy sources such as large-scale storage of hydrogen. For example, in Austria, if 100 % of the electricity generated would come from renewable sources, storage with capacity over 100 times greater than the potential offered by pumped storage will be needed[36].

25 » WHAT ROLES DO GAS STORAGE FACILITIES PLAY FOR THE FUTURE CHALLENGE OF CONSTANT GAS QUALITIES?

When blending hydrogen, one of the main challenges is to maintain a constant gas quality with a defined range of hydrogen content. Since the main production of renewable hydrogen would take place during summer when there is lower energy demand, hydrogen supplywould be much higher than during winter. Underground gas storage will not only shift hydrogen volumes from summer to winter, but will also balance the concentration. When precise hydrogen levels need to be achieved, membrane technologies could improve this process even further.

34 Landinger et al. (2014) 'HyUnder: Update of Benchmarking of large-scale hydrogen underground storage with competing options'

35 "The interface between two fluids, for instance hydrogen and groundwater, is stable or unstable depending on the relative magnitudes of the viscous, interfacial, and gravitational forces and the direction of movement of the interface. Instability occurs in horizontal flow when the mobility of the displacing fluid is greater than the mobility of the displaced fluid. This instability may cause long fingers of the displacing fluid to penetrate the displaced fluid, hence the term 'fingering'. Such is the case when hydrogen or natural gas displaces water." (Paterson, 1981)

36 Vienna University of Technology, ESEA/EA (ed.): 'Super-4-Micro-Grid', research project final report, Vienna 2011

26 » WILL THE EXISTING GAS STORAGE CAPACITY IN EUROPE BE SUFFICIENT TO COVER THE FUTURE STORAGE AND FLEXIBILITY DEMAND FOR HYDROGEN?

According to BloombergNEF (2020)[37], in the scenario of a strong and comprehensive climate policy in force to limit global warming to 1.5 degrees, approximatively 700 million metric tons of hydrogen could be used globally in 2050. If 20 % of this annual hydrogen demand would be stored, they assumed that the equivalent of 14,000 salt caverns would need to be built at a cost of $637 billion. This massive investment needs to be compared with the 101 already existing salt caverns which currently store natural gas globally[38]. Among them, 51 sites[39] are located in the EU27 and could be repurposed for hydrogen at lower costs.

To meet the future European hydrogen storage demand, additional salt cavern projects will need to emerge in the future. A recent study by Clagayan et al. (2019) estimated an extensive technical storage potential for salt caverns across the continent, both onshore and offshore[40]. As represented in Figure 2, Germany is the country with the highest technical storage potential, especially located in onshore salt caverns in the north of the country.

In case salt caverns are not available, depleted fields and aquifers constitute the next best large-scale solutions for hydrogen storage.

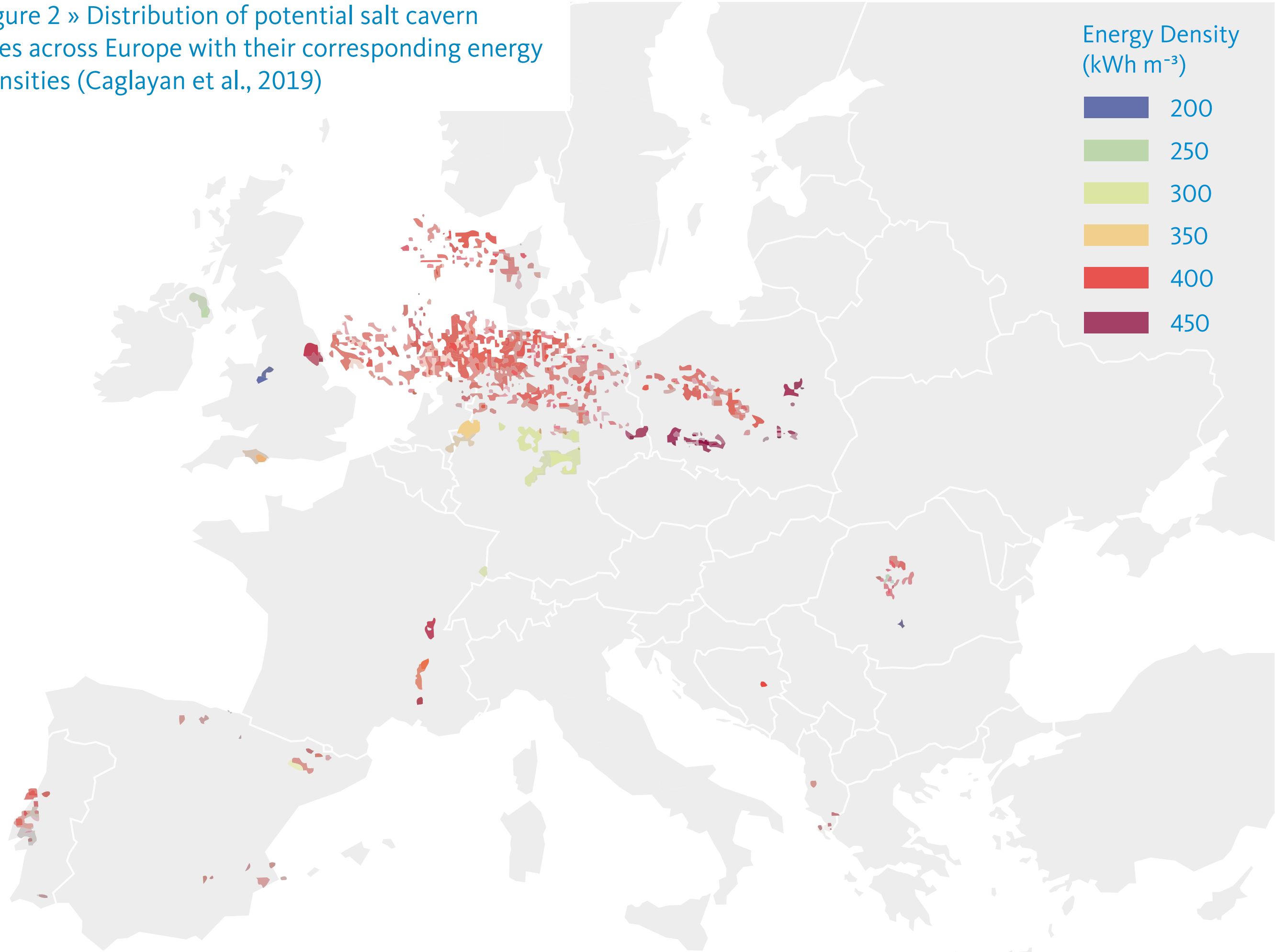
37 BloombergNEF: Hydrogen Economy Outlook. Key messages, March 30, 2020

38 According to the list of underground gas storages by International Gas Union.

39 Gas Infrastructure Europe:. Storage database, December 2018

40 Caglayan et al.: Technical potential of salt caverns for hydrogen storage in Europe., Oktober 2019

Figure 2 » Distribution of potential salt cavern sites across Europe with their corresponding energy densities (Caglayan et al., 2019)



27 » IS IT SAFE TO STORE PURE HYDROGEN OR HYDROGEN BLENDS?

Underground storage facilities benefit from several advantages to cope with hydrogen such as the absence of oxygen underground or the high fluid pressure. Hydrogen storage in salt caverns is already a proven technology with several sites in the North of England and in the United States. The tolerance of depleted gas fields for hydrogen blending of up to 10 % has been successfully tested on existing facilities without any negative influence on safety[41]. Furthermore, in case hydrogen blending is foreseen, all the consequences of the hydrogen admixture especially on the integrity of the storage facility (seals and components installed, compatibility of identified materials, etc.) are carefully assessed before injection. This is done to ensure that there will be no migration out of the reservoir and alteration of the rock.

41 Tichler, A., Zauner, A., Baresch, M., De Bruyn, K., Friedl, C., Furtlehner, M., Goers, S., Lindorfer, J., Mayerhofer, J., Reiter, G. & Schwarz, M. (2017): Underground Sun Storage: Final Report Public, January 2020.

ABOUT THE AUTHORS

The European Network for Transmission System Operators for Gas (ENTSOG) was founded in line with Regulation (EC) 715/2009 and has played a key role in facilitating integration of the European gas markets, ensuring technical interoperability and providing security of supply by gas infrastructure planning. Looking forward, ENTSOG is contributing to the net-zero decarbonisation by 2050, in particular, by the integration of renewable and low carbon gases via future-proof gas transmission pipelines, in line with the EU energy and climate goals. More information on ENTSOG can be found on our website – www.entsog.eu or contact info@entsog.eu

Gas Infrastructure Europe (GIE) is the association of the European gas infrastructure operators. Its members operate the gas transmission networks, underground storage facilities, and LNG terminals. GIE has around 70 members from 27 European countries, thus embodies the multiple transitional decarbonization pathways of the EU regions. GIE members are committed to help deliver EU's goal in being the first continent achieving climate neutrality by 2050. For further information, please visit www.gie.eu or contact gie@gie.eu

Hydrogen Europe is the European association representing the interest of the hydrogen and fuel cell industry and its stakeholders. It promotes hydrogen as an enabler of a zero-emission society. With more than 260 companies and 27 national associations as members, our association encompasses the entire value chain of the European hydrogen and fuel cell ecosystem collaborating with the European Commission in the Fuel Cell Hydrogen Joint Undertaking. For further information, please visit www.hydrogeneurope.eu or contact secretariat@hydrogeneurope.eu

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