CHEMICAL ENGINEERING TRANSACTIONS

VOL. 105, 2023

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: David Bogle, Flavio Manenti, Piero Salatino

ISBN 979-12-81206-04-5; **ISSN** 2283-9216

DOI: 10.3303/CET23105012

Preliminary Studies on Methane-Hydrogen Blends in Natural Gas (NG) Pipelines –A Case History for Technical Evaluation in an Existing Distribution Network to Identify Barriers and Enablers

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Low-carbon/carbon-free fuels are shaping how will be the future of energy utilization in hard-to-abate sectors such as transport, heavy industries, power generation, building sector, and seasonal energy storage. This is projected to contribute to a 10% CO_2 emission reduction by 2050. Storage and transportation are key elements in a hydrogen economy value chain which, will connect production facilities to end users. Transporting hydrogen in liquid form, via trucks and ships, has more techno-economic challenges than transport through pipelines. Therefore, the transportation and distribution of hydrogen purely through new pipelines and/or blending hydrogen with natural gas by repurposing existing Natural Gas (NG) pipelines are seen as more promising. Refurbishing pipelines is estimated to be about 33% of the cost of new infrastructure. Existing NG Transmission System Operators (TSOs) and Distribution System Operators (DSOs) are evaluating the technical readiness of their infrastructures. In this paper, the preliminary studies focus on the feasibility of extending the usage of current pipelines for the distribution of H_2-NG blends. The study evaluates the H_2-readiness of pipelines in a distribution network in Sicily for its technical adaptability, regulations, and legislation in this local zone. The study provides a review of the different steel types, microstructures, cathodic over-protection, and their impact on Hydrogen Embrittlement (HE). The effect of the interaction of HE gaseous inhibitors such as O_2, CO, and SO_2 is presented together with the counter-reactive effect of water vapor in the presence of SO_2. Based on the case history, the barriers and enablers are critically evaluated for different H_2-NG blends until a 10% maximum value which is a threshold in many EU countries.
Keywords: Hydrogen blend, transport/distribution pipelines, energy policy, Hydrogen embrittlement

1. Introduction

The European Union's (EU) hydrogen strategy envisages that H_2 will play an important role in the future of integrated energy systems. It will also promote electrification with the use of renewable energy sources and strive to attain higher efficiency and transition from a linear to a circular consumption model by adopting circular policies. Hydrogen usage in this new scenario is that of an energy carrier, raw material for different industries, and possible fuel produced utilizing renewable energy. The production of H_2 – now largely based on fossil fuels – would need to be decarbonized, which will require a massive increase in the production of renewable electricity (EPRS, 2021). More than 50% of domestic residential buildings are connected by gas grids in countries like USA, UK, Italy, and Australia (Jamie Speirs et al., 2017), thus making it a critical sector to decarbonize the building energy bulk. In Italy, the Ministry of Ecological Transition - by its DM 3/6/2022 - has updated the "Technical rule on the chemical-physical characteristics and the presence of other components in fuel gas", approved with the Decree of the Minister of Economic Development May 18, 2018. The DM regulates the first precautionary limit value of 2% for the introduction of hydrogen into the networks that do not compromise the treatment, storage, and/or use of natural gas. The objective, as envisioned by the National Recovery and

Paper Received: 4 March 2023; Revised: 20 March 2023; Accepted: 26 April 2023
Please cite this article as: Baby B.A., Beccali M., Ferraro M., Poma G., Bonanno S., 2023, Preliminary Studies on Methane-hydrogen Blends in Natural Gas (NG) Pipelines – a Case History for Technical Evaluation in an Existing Distribution Network to Identify Barriers and Enablers, Chemical Engineering Transactions, 105, 67-72 DOI:10.3303/CET23105012

Resilience Plan (PNRR) is to introduce H_2 while ensuring the highest levels of safety for users, population, and the environment. The Ministry plans to extend the injection limits further, based on the results of the studies and experiments in progress (MINISTERO DELLA TRANSIZIONE ECOLOGICA, 2022). However, currently, there is no organic legal framework for the large-scale injection of "pure" H_2 into the natural gas transmission network in Italy (Strockl, 2021). This paper conducts a preliminary analysis of a local Distribution System Operator (DSO) based in Italy and feasibility studies on the system's H_2 injection readiness. The first stage evaluates: i) the demand profile and typology of the users in the total network and a test subsection chosen ii) material study and suitability review considering maximum pressure, HE, and cathodic protection limits iii) further analysis of the need for compressors and storage for low-pressure distribution side iv) Regulations as applicable to the European and Italian markets is briefly reviewed. Finally, the gaps in knowledge, technology, and financial support systems (public and private) are categorized as enablers and/or barriers for the sector.

2. Materials and methods

The hydrogen value chain begins with H_2 production by electrolysis or steam reforming method. The produced H_2 is then stored and transported to the end users to be utilized for electrical or thermal energy needs or as pure H_2 stream for industries such as the chemical/fertilizers sector. A well-established hydrogen ecosystem is in its nurturing stage, and a plethora of studies are conducted in different areas from production, transportation, and storage to end-user utilization. The study conducted in this paper evaluates the existing distribution pipeline infrastructure network for NG which connects the high-pressure Transmission System to the end users. Detailed information on materials used, demand distribution, and typology of users is also reported. For incorporating H_2 into the system, a feasibility analysis was done, based on material compatibility, and methods of avoiding/mitigating HE. The need for additional components, such as storage and compression stations, is investigated, and further recommendations are stated.

3. Results and Discussion

3.1 Gas Demand Distribution and User Typology

The DSO operates year-round to supply NG to the end user under Medium Pressure (MP - 0.5 bar) and Low Pressure (LP - 30 mbar). The annual consumption of users in the city of Palermo is categorized as shown in Figure 1.

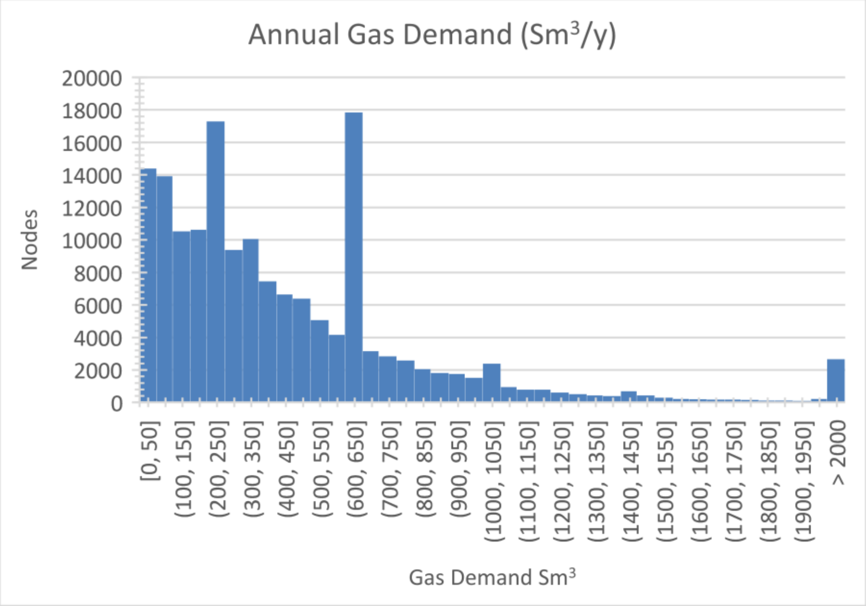

Figure 1: Gas Demand Profile

To closely evaluate the operational parameters, such as pressure and flow velocity, a sub-section of the whole network has been identified. The sub-section is a representation of the user profile category for the total network considered. The profile classification is shown in Figure 2. The individual user consumption is masked, and a profile range shows a representation of annual demand in volume (Sm^3/y). The user profile variation is based on the type of consumption. Unlike other common European – Italian scenarios, the usage of gas is classified for Space heating (SH), Hot water (HW), Cooking, and other applications.

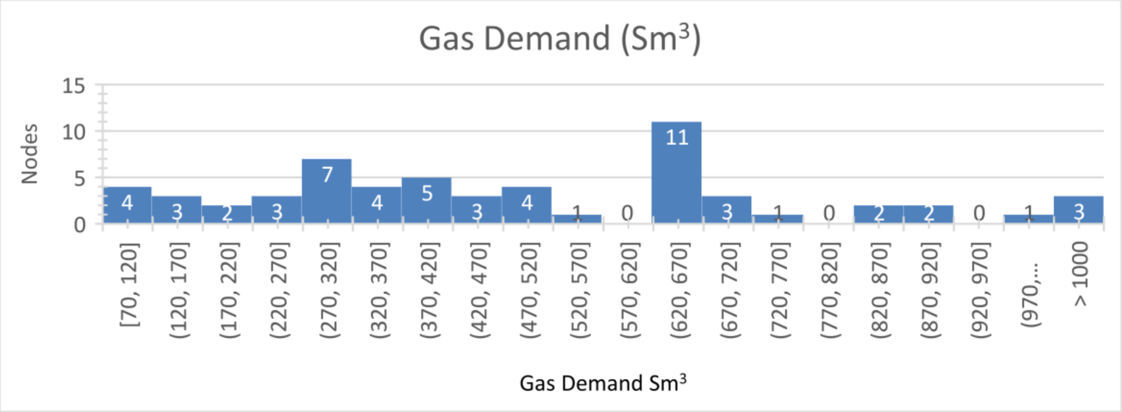

Figure 2: Gas Demand Profile for the network subsection

In Figure 3 the end-user application for the network subsection considered is depicted. Most of the users (68%) use NG for all three applications of SH, HW, and cooking, while 18% use it only for Cooking and HW while 10% of consumers are just for cooking purposes. Sicily, having a Mediterranean climate, does not experience very cold winters which makes more than a quarter of customers exclude the usage of space heating. The change in public attitude to rely on more efficient electric heating is also another driving force in this scenario.

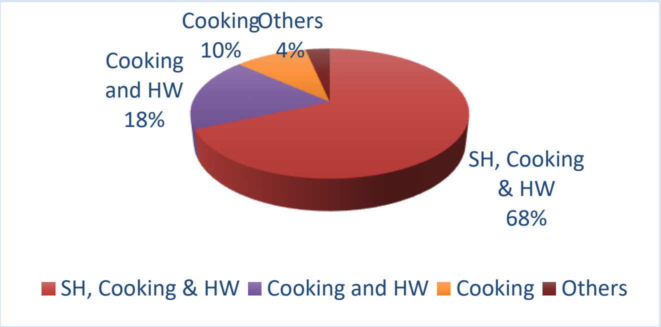

Figure 3: End-user typology for the network subsection

3.2 Materials Study

Using the existing pipeline, the steel used is not chemically inert to NG-H_2 mixture. HE and Maximum Operating Pressure (MOP) are two main material-related limitations in H_2-NG blending. Appropriate grade of steel is critical for prolonged existence of pipelines. The harder the steel and the rougher its surface, the more susceptible is to HE. This process occurs when hydrogen atoms formed on the metal's surface starts diffusing into the metal lattice, instead of forming H_2 molecules on the material's surface. The H-atoms will then recombine with molecules inside the material, resulting in gas bubbles or material separation (cracking) leading to embrittlement. Defects in crystal lattice are locations with high mechanical stresses, they are more vulnerable to HE and hydrogen-induced cracking. Carbon steels display reduced fracture resistance and accelerate crack propagation even at low partial pressure. In the case study considered here, the material used is, predominantly, L245-grade steel. General corrosion appeared on the L245 steel surface in H_2S saturated stratum water, only at 75˚C temperatures which makes the material suitable for H_2-NG transportation (Han et al., 2016).

The maximum pressure that the pipeline can withstand is plotted against different Safety Factor (SF) depending on the environment, pipeline operating conditions, material, and design considerations as in Eq (1),

$$P_{max} = \frac{2\sigma_{min}s}{d_0 SF} \tag{1}$$

where P_{max} is the maximum internal pressure, σ_{min} is Specified Minimum Yield Strength (SYMS) of the pipe, s is the wall thickness and d_0 is the outer diameter. The case study considered here has pipes of two different outer diameters based on gas pressure limits classified by UNI CIG 9165:2020 and the (specie VI) MP ranges as 100 mm and 150 mm. In Figure 4, for the two different outer diameters of the existing infrastructure, the plot shows the variation of the maximum internal pressure according to Eq (1) for increasing safety factor. All the pressure values are much greater than the values usually encountered in the test subsection of the network (maximum operating pressure in the network is 0.5 bar). So, the distribution side proves to be less sensitive to maximum pressure limits based on the material.

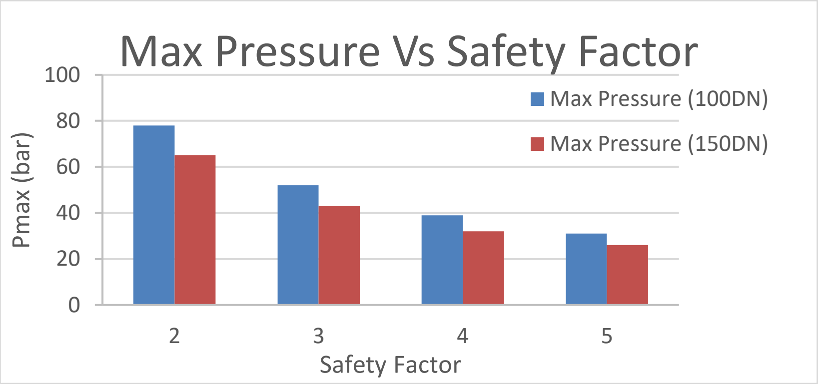

Figure 4: Maximum pressure Vs Safety factor plot

3.3 Hydrogen embrittlement inhibitors

HE is one of the major materials-related problems, posing challenges to the transport of H_2-NG blend. HE has been studied for a long time as a critical aspect in other applications in oil and gas sector such as handling sour gas, with up to 13% H_2, to safeguard pipeline networks (Mottley & Pfister, 1963).

The diffusion of H_2 to the crystal lattice occurs in two ways: at higher temperatures H_2 in a combined state reacts with the surface carbon present in steel to form methane and leaves microcavities as a result. This diffusion of H_2 is reversible if microcavities are not formed. The phenomenon is called a “Hydrogen attack”. HE occurs at close to ambient temperature leading to diffusion of H_2 to the lattice of steel and leading to mechanical properties derating causing deformation due to stress concentration or fatigue in pre-existing defects or plastic deformations (Barthélémy, 2007). The use of gaseous inhibitors is a possible solution for existing pipelines; the effect of microstructure is discussed further below.

Gaseous inhibitors

These are gases blended along with the gas mixture (H_2-NG) to prevent the diffusion of H_2 into the surface of the pipe material and eliminate the possibility of degradation. H_2 with additives like oxygen considerably reduces the HE due to the higher electronegativity of O_2 in comparison to H_2 (Michler et al., 2012). This suppresses the catalytic cavity of hydrogen disassociation to the iron surface. The use of carbon monoxide also demonstrates a positive impact in reducing HE intensity when mixed with H_2 gas. Oxygen atoms in CO are absorbed to the surface and carbon atoms, oriented to the surface, prevent further H_2 dissociation (Atrens et al., 2023). Methane and Nitrogen (N_2) do not seem to have any appreciable effect (Staykov et al., 2014). But in contrast, some impurities, like CO_2 and especially H_2S, have an accelerating effect on HE (Makarenko et al., 2000). Sulfur Dioxide (SO_2) also has an inhibiting effect. The presence of water vapor in the pipeline will prove to be counter-reactive aggravating, the HE risk by creating an acidic medium in the presence of additives like SO_2 and CO (Barthélémy, 2007). Further studies need to be performed to understand the interactions of gas mixtures in actual scenarios and the effect of the partial pressure of each gas on HE.

Effect of Microstructure and Heat Treatment

Hydrogen uptake in steel depends on Body Centered Cubic (BCC), Face Centered Cubic (FCC), Hexagonal Close Packed (HCP) crystalline structures, heat treatment, and mechanical properties of the pipeline alloy. Martensitic structures are more prone to failure, Ferrite structure has intermediate performance while Austenitic alloy has superior resistance to, HE. In Austenitic stainless steels, elements such as Ni, C, and Mn stabilize the structures reducing the risk of HE (independently of microstructure). Ferritic steel has the advantage of the presence of vanadium and other rare-earth elements in the microstructure which can trap H_2 and prevent HE and further crack propagation (Blanchard et al., 2020). Tempering performed at high temperatures, which gives milder steel, is beneficial to its HE behavior. In the same way, strong quenching has a favorable effect. Finally, for carbon steels, normalization treatment in the final state has a positive effect, i.e., it reduces the risk of HE (Blanchard et al., 2020). For carbon steels, the hardness of the welded area and heat-affected zone should be limited. In the case of Austenitic stainless steels, the formation of ferrite should be limited. As for steels, the HE sensitivity may depend on the exact chemical composition, heat or mechanical treatment, microstructure, impurities, and strength; and the whole concern should be validated by HE susceptibility testing.

3.4 Cathodic protection

Corrosion of pipeline surfaces buried underground can occur due to the electric potential difference between the pipeline (anode) and soil (cathode). Electric insulation is provided, in addition to a sacrificial anode or impressed current, to protect the pipe from external corrosion. The investigated case-study here uses a triple coating of polyethylene and Impressed Current Cathodic Protection (ICCP) stationed at different locations of the network. The length of the pipeline protected by the ICCP power station is over 15 km. While the range of cathodic protection in the studied zone varies from -2 to -1.6 V depending on the month. Cathodic overprotection can lead to Hydrogen Assisted Cracking (HAC) and values below -1.2 V (Cazenave et al., 2021).

3.5 Compression and storage in the Distribution side

Pressure drop is a major issue, on the transmission side, because of long-distance H_2 transport with need for critical points for H_2 injection, compressors, storage stations, and flow meters. This can result in different compositions affecting the gas quality at the end-users. The distribution side is less susceptible to major pressure drop variations while most networks, as in the case studied, lack storage/compressor units. Also, the quality of downstream gas will have to be measured and regulated for metering and invoicing purposes. H_2 has a higher heating value (HHV) of 10 MJ/S^3, whereas the HHV of NG injected into the given network is in the range of 39.27 to 39.9 MJ/Sm^3 (Algerian and Libyan gas) which indicates the need for compressing and transporting almost three times more H_2 to meet the energy demand (Guzzo et al., 2022). The density of H_2 is one-nineth of NG therefore the flow velocity can be three times larger than NG making the pressure drop comparable to NG (Haeseldonckx & D’haeseleer, 2007).

The short-term storage of gases in pipelines is called linepack and this enables uninterrupted gas flow to meet variable demand cycles in a network. Further studies should be done to analyze the gas grid linepack flexibility and optimize the need for storage tank/ H_2 pressure vessels based on historical consumption patterns. Studies show that 25% (Shirvill et al., 2019) to 30% (Lowesmith et al., 2011) H_2-NG mixture do not pose major safety problems because of increasing the pressure ranges as it acts more like methane. For volume fractions more than 40% it may pose a major safety hazard caused by overpressure. Fluctuating H_2 concentrations can drastically alter the threshold values of overpressure, flame propagation, and temperature rise in an explosion (Emami et al., 2013). This has a considerably lower impact for lower H_2 injection rates.

4. Regulatory Framework

A framework of policies is quintessential for the complete adoption of Hydrogen across all sectors such as energy and power, long-haul transport, and hard-to-abate industries such as steel, chemical, and glass manufacturing. With close to 2000 projects across more than 85 countries worldwide that are declared, planned, and at various stages of implementation, the Hydrogen economy is becoming a reality. Regulations and directives pave a smoother and standardized transition to meet the global target of keeping the temperature increase to 1.5°C above pre-industrial levels, according to Paris agreements. The European hydrogen backbone has currently participation of thirty-one energy operators joining hands to develop a 53,000 km pipeline network comprising 60% refurbished pipelines by 2040 (EHB, 2022). The permitted percentage of H_2 in the system varies as 10% (Germany), 6% (France), 5% (Spain), 4% (Austria), 2% (Italy, Belgium, Lithuania, Switzerland) 1% (Finland) to as low as 0.1% (Latvia, Sweden) (Erdener et al., 2023). Germany has over 100 projects, the Netherlands has 40 projects, France with 19 projects, and Italy has 18 projects at various stages of execution (IEA, 2022). The European regulatory framework ISO/TC 197 (SC1), is a proposal for a "Methodology for determining the GHG emissions associated with the production and transport of H_2", to find a three-part standard covering production, conditioning, and transport. ISO 19885 covers fuelling protocols for hydrogen vehicles and was initiated in early 2021 targeting the end by 2024. CertifHy™ is now developing an EU Voluntary Scheme for the certification of hydrogen as RFNBO (Renewable Fuel of Non-Biological Origin) in accordance with the new European Renewable Energy Directive giving additionality, temporal correlations making national borders a geographic limit to correlations. In the near future, the impact it has on industries must be further analyzed considering also how it will attract investments in the H_2 sector.

5. Conclusions

Hydrogen is an energy carrier that has a pivotal position in the energy sector at present. For this segment, which is developing to reach the scale and magnitude it has to grow to, working against fast-closing targets poses a lot of challenges and opportunities. From the discussion above the enablers and barriers of the sector are summarized below. The enabler of the sector, that support the growth of this sector are i) joint cooperation at various focuses from stakeholders such as government bodies and policymakers, industry, and academic sectors. ii) Repurposing existing pipelines offer a saving of up to 70% when compared to erecting a new pipeline.

iii) Carbon pricing hit up to € 100/tonne of Carbon emitted incentivizing low-carbon technologies and encouraging a switch to cleaner energy. iv) Financial, aid in the form of tax credits, hydrogen banks, and more private sector participation in giving solidarity to Hydrogen technologies will support further expansion of this sector. On the contrary, the barriers to full deployment of H_2 utilization needs to be resolved from the grass root, such as i) a fully established infrastructure to meet the future needs of H_2 demand ii) the knowledge gap in complex gas mixture behavior in distribution networks, unlike long-distance straight pipelines, at valves, bends, etc. ii) The need for upgrading end-user equipment such as boilers and gas burners for higher percent H_2 vol%. iii) gas quality measurement and tariff standardization across different users. iv) The additional safety measures against possible explosions to be put in place and assessing the willingness of existing end-users.

Acknowledgments

The research is supported and co-funded by AMG Energia S.p.A. and Istituto di Tecnologie Avanzate per l'Energia "Nicola Giordano", Consiglio Nazionale delle Ricerche (CNR ITAE).

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