Determining Energy Capacity for H_2 in existing NG pipelines

Summary Report, November 2023

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Table of Contents

Abbreviations and acronyms

H_2	Hydrogen
NG	Natural Gas
GHG	Greenhouse Gas
lowcal	Low calorific value
hical	High calorific value
MJ/nm^3	Megajoules per normal cubic metre
Z	Compressibility factor
Re	Reynolds number
V-EQ	equal velocity
DP-EQ	equal pipeline capacity
E-EQ	equal energy transmission
RP	Recommended Practices
API	American Petroleum Institute
ISO	International Organization for Standardization
GERG	European Gas Research Group
AGA	American Gas Association
EIG	Energy Institute Guidelines
PRS	Pressure Reduction Station
LOF	Likelihood of Failure
FIP	Flow Induced Pulsations
FIT	Flow Induced Turbulence
FIV	Flow Induced Vibrations
AIV	Acoustic Induced Vibrations

Introduction

Transporting hydrogen or hydrogen blends via natural gas pipelines is an essential measure to reduce GHG emissions. One of the known effects of replacing natural gas with hydrogen is the potential decrease in energy capacity. Thus, understanding the flow-related impact of repurposing natural gas pipelines for hydrogen blend service and 100% hydrogen, becomes a critical aspect to determine different energy capacity scenarios.

Corridors between Africa and Europe, as well as the North Sea region, are closely linked to the European Hydrogen Backbone, which is based on new and existing pipelines for the development of a pan-European hydrogen backbone. It is evident that hydrogen is expected to be gradually introduced into existing pipelines, since these can be repurposed to transport hydrogen instead of constructing new dedicated hydrogen pipelines, therefore accelerating the decarbonisation goals while supporting the transition towards renewables.

There is still a need to research and document integrity risks when introducing hydrogen. Existing work includes the Energy Institute guidelines for the industry to deal with risk of vibration and pulsation[1] as well as the findings of HyDelta on the integrity impact of increasing hydrogen speed. Regarding erosion, it is generally concluded that hydrogen has a higher erosion potential compared to natural gas; important references include DNV's recommended practice to manage sand production and erosion DNV-RP-O501/6/ and the American Petroleum Institute (API) recommended practice API RP 14E.

Objectives

The main objective of the project was to study the flow-related impact of repurposing natural gas pipelines for hydrogen blended with natural gas or for pure hydrogen, considering that, in general, the velocities need to be increased to compensate for the lower energy value per cubic meter. The project aimed to determine the impact of using existing natural gas transmission networks for transporting specific concentrations of hydrogen, evaluating not only the energy capacity effect, but also some integrity aspects, as well as the physical properties.

One of the goals was to better understand why integrity-related risks or changes in capacity could occur under certain conditions and possible scenarios when transporting hydrogen in the natural gas network. Blending hydrogen with natural gas implies changing the composition, hence the gas properties, some of which are studied here. Another objective was to try to meet the requirements needed to maintain the same energy capacity of the network by increasing the fluid velocity and subsequently the flow in the pipe.

[1] Energy Institute., 2008. Guidelines for the Avoidance of Vibration Induced Fatigue Failure in Process Pipework (2nd Edition)

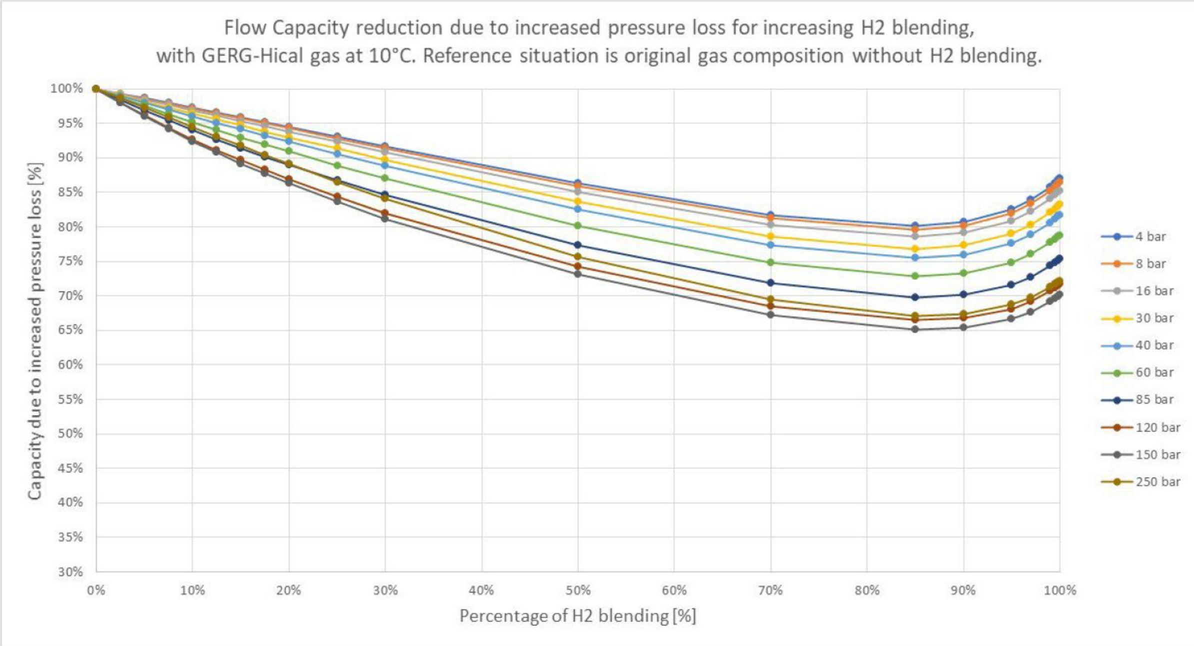

FIGURE 1. POTENTIAL LACK OF PIPELINE HYDRAULIC FLOW CAPACITY, CAUSED BY INCREASED PRESSURE DROPS WHEN TRANSPORTING SIMILAR AMOUNTS OF ENERGY (CURVE SHOWN FOR GERG-HICAL COMPOSITION).

Scope of work

The definition of the project starts with understanding the nature of the gas that is typically transported in the gas transmission network. The calorific value varies depending on the type of natural gas. Therefore, three different compositions of natural gas covering a considerable range of gross heating values were assessed: GERG-lowcal (e.g. biomethane), GERG-hical (e.g. LNG gas) and Groningen gas. None of the compositions of the reference natural gases considered contained hydrogen. Method ISO6976[2] was used to calculate calorific values in this study. Furthermore, different pressure conditions were studied in order to cover distribution (4-30 bar), transmission (40-80 bar) and storage (120-250 bar). The temperature was fixed on 10 degrees Celsius for this study.

After identifying the types of natural gas and the pressures of interest, specific hydrogen concentrations were defined; representing potential real scenarios of blending defined in mol% (5%, 10% and 20% hydrogen), as well as 100% hydrogen. The last part of the definition of the project consisted in choosing 3 operational transition scenarios of repurposing: equal (maximum) velocity (V-EQ), equal pipeline capacity (DP-EQ) and equal energy transmission (E-EQ); the latter being the reference scenario as it assumes that downstream clients have the same demand for energy as in natural gas when transporting hydrogen. A schematic of the fluid velocity effects of the different scenarios is shown in Figure 2.

[2] ISO 6976:2016. Natural Gas – Calculation of calorific values, density and Wobbe indices from composition

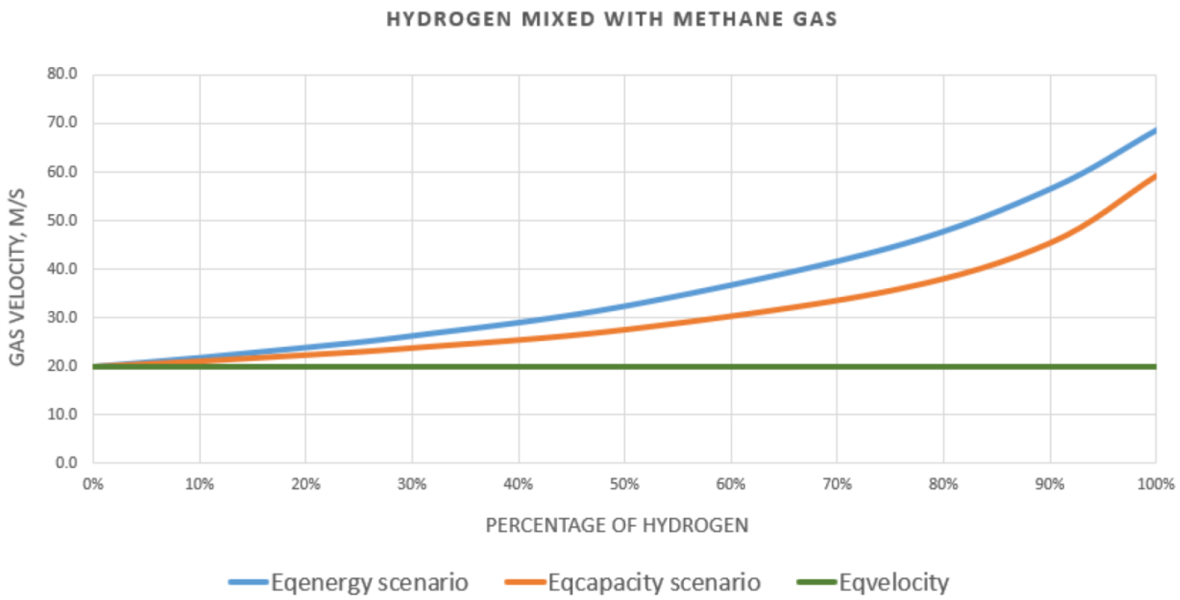

FIGURE 2. SCHEMATIC EXAMPLE OF THE EFFECT ON MAXIMUM REQUIRED FLUID VELOCITY OF THE 3 SCENARIOS (BLUE: EQUAL ENERGY CAPACITY, ORANGE: EQUAL CAPACITY AND GREEN: EQUAL VELOCITY)

For the results, a ratio was used to refer to the rate evaluating the impact of a certain gas, capacity, or integrity related property. A ratio of 1 indicates no change, a ratio lower than 1 indicates a decrease and a ratio higher than 1 indicates an increase. Rejection criteria were also used for integrity-related risks.

The following velocity related integrity risks were investigated:

- Flow induced pulsations
- Flos induced turbulence
- Flow noise risk or risk of acoustic induced vibration
- Flow induced vibration of intrusive elements
- Erosion

In addition to velocity related integrity risks, the capacity impact of increased velocities were investigated as part of this work.

Capacity assessments or the different hydrogen mixtures were performed for the following scenarios:

- Capacity of pipelines and/or overall energy transmission system
- Capacity of pressure reduction lines or station

Literature and background information

Pipework vibration

The Energy Institute Guidelines were developed to deal with the risk of vibration and pulsation[3]. These have been used to perform qualitative and quantitative risk assessments of process pipework in the gas and oil industry. This approach for assessing pulsation risk is limited as it does not present a

[3] Guidelines for the Avoidance of Vibration Induced Fatigue Failure in Process Pipework – Energy Institute, second edition 2008

method for conducting an analysis to predict the pulsation levels which can arise when a natural frequency of a branch is excited.

The HyDelta report presents a formula to estimate the change in pulsation levels after changing from natural gas towards full hydrogen. This formula assumes that power losses arise from visco-thermal forces but seem to neglect other forms of power loss. This consideration may need to be extended to include other sources of power loss.

Erosion

This study used the recommended practice DNV-RP-O501[4], a guide to evaluate the risk of erosion in pipework; more specifically, how to manage the consequences of sand produced from oil and gas reservoirs. It was used because it considers the effect of the decrease in drag in hydrogen blends. Furthermore, to estimate the erosional velocity, which is the flow velocity under which it is assumed no erosion would occur as a common erosion control method, the API RP 14E equation has been traditionally used. Nevertheless, some operational parameters are not considered in this equation such as flow regime, sand production rate and material properties.

Other relevant findings from the literature review, related to erosion, are a theoretical investigation of the maximum hydrogen speed in pipelines[5], which classifies different zones describing the behaviour of particles in a fluid, and the outputs from HyDelta[6] on the impact of high speed hydrogen flow on system integrity and noise, stating that the most uncertain mechanism preventing achieving the desired flow velocity is erosion.

Impact on physical properties and flow related parameters

Since hydrogen has approximately 3 times lower gross calorific value than natural gas (depending on the composition); to compensate for the energy content when transporting hydrogen at atmospheric conditions, gas flow must be increased, specifically the hydrogen velocity, roughly by a factor of 3. The influence of hydrogen blending on the calorific value is a linear effect, the gross calorific value of hydrogen being about 12.75 MJ/nm^3 (figure 3). Another important indicator of the energy content is the Wobbe Index, which depends on the gross calorific value but also the relative density of the gas. Due to the fact that the relative density decreases non-linearly as more hydrogen is blended, the small density becomes significant only above 70% hydrogen, when the Wobbe Index starts to increase.

TABLE 1. HEATING VALUES AND WOBBE INDEX FOR THE DIFFERENT GAS COMPOSITIONS. THE STANDARD CUBIC METER SM^3 DEFINITION IS 15°C/15°C FOR COMBUSTION/METERING AND 1.01325 BAR(A), AND THE NORMAL CUBIC METER NM^3 IS 25°C/0°C AND 1.01325 BAR(A).

Composition	Gross heating value (GHV)	Wobbe index
GERG-hical	41.31 MJ/Sm^3 or 43.55 MJ/nm^3	52.45 MJ/Sm^3 or 55.29 MJ/nm^3
GERG-lowcal	36.95 MJ/Sm^3 or 38.96 MJ/nm^3	48.85 MJ/Sm^3 or 51.50 MJ/nm^3
Groningen	33.26 MJ/Sm^3 or 35.06 MJ/nm^3	41.44 MJ/Sm^3 or 43.68 MJ/nm^3

[4] DNV recommended practice: DNV-RP-O501: Managing sand production and erosion, (2015)
[5] Maximum Hydrogen Speed in Pipelines – Theoretical investigation, CR2121-12, von Karman Institute for Fluid Dynamics, P. Planquart, M.T. Scelzo 2121
[6] HyDelta: WP1E – Impact of high speed hydrogen flow on system integrity and noise, TKI2020-HyDelta, N.G. Diez 2020

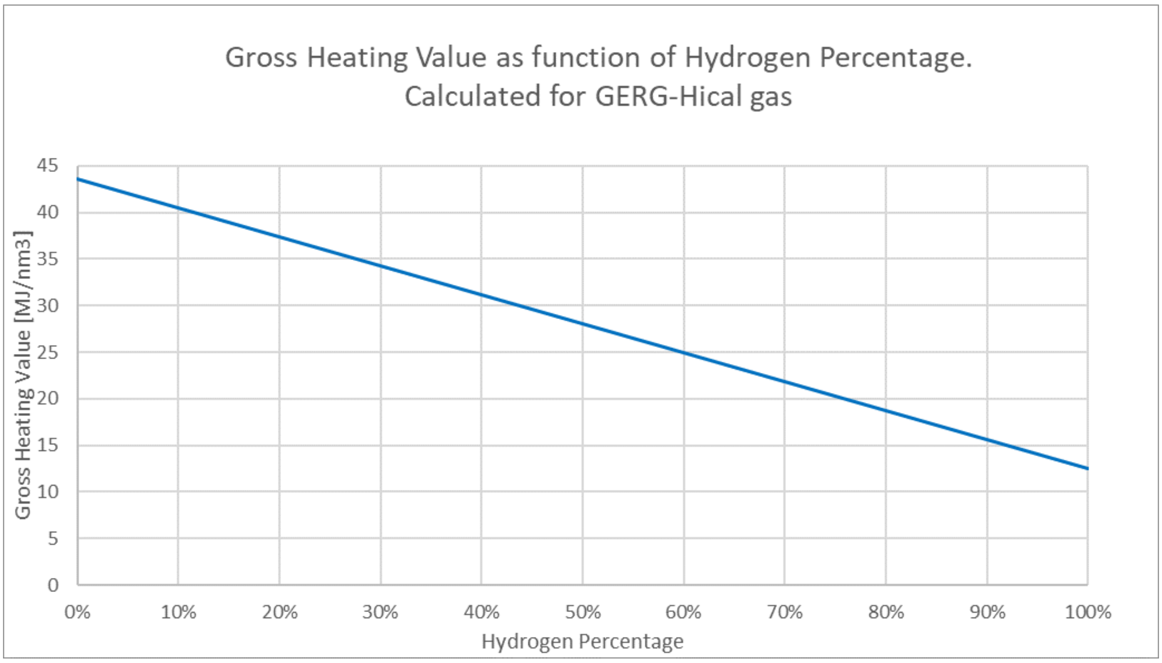

FIGURE 3. VARIATION OF GROSS HEATING VALUE GHV FOR GERG-HICAL GAS WHEN BLENDING HYDROGEN

At the same pressure and temperature, hydrogen has a lower density than natural gas. Consequently, as more hydrogen is blended with natural gas, the density decreases by a factor of about 9 to 12, with the largest decrease at higher pressures. As hydrogen is less compressible than natural gas, it is observed that the compressibility factor Z becomes closer to 1.0 as more hydrogen is blended and larger than 1.0 above 70% hydrogen. This conclusion is met at different pressure values; however, depending a reverse non-linear effect is observed between 150 and 250 bar. Equations from AGA8[7], as well as GERG2008[8] were used to calculate density and compressibility.

The comparison of viscosity at different pressure shows that the dynamic viscosity decreases as more hydrogen is blended with natural gas, with a much more significant decrease at higher pressures. This property is important for the subsequent calculation of the Reynolds number Re, which helps predict flow conditions (i.e., laminar or turbulent) by measuring the ratio of inertial forces to viscous forces. Two methods were employed to calculate dynamic viscosity: GasVLe/TRAPP[9] and ISO 20765-5[10].

As one of the main objectives of this work has been to evaluate the fluid velocity required for equal energy capacity, it has already been stated that at atmospheric conditions, the required fluid velocity to maintain energy capacity when transporting hydrogen is approximately a ratio of 3; but this is highly dependent on the energy content of the reference natural gas, therefore the composition. Even today, the fluid velocity is already higher for high calorific gases (e.g. GERG-hical) than for low calorific gases (e.g. GERG lowcal); which results, for 100% hydrogen, in a fluid velocity increase between 2.5 and 5.5, for the three gas compositions used in the analysis, depending on the pressure and gas composition.

[7] American Gas Association., 2017. AGA Report No.8, Part 1, Thermodynamic Properties of Natural Gas and Related Gases, DETAIL and GROSS Equations of State (3rd Edition)
[8] GERG., 2008. The GERG-2008 wide-range equation of state for natural gases and other mixtures: An expansion of GERG-2004, October 2012, Journal of Chemical & Engineering Data 57(11):3032-3091
[9] NBS: A modified form of the NBS program TRAPP
[10] ISO 20765-5:2022. Natural gas — Calculation of thermodynamic properties — Part 5: Calculation of viscosity, Joule-Thomson coefficient, and isentropic exponent

It is important to mention that taking into account the compressibility effects, fluid velocity should be increased further as hydrogen blending increases.

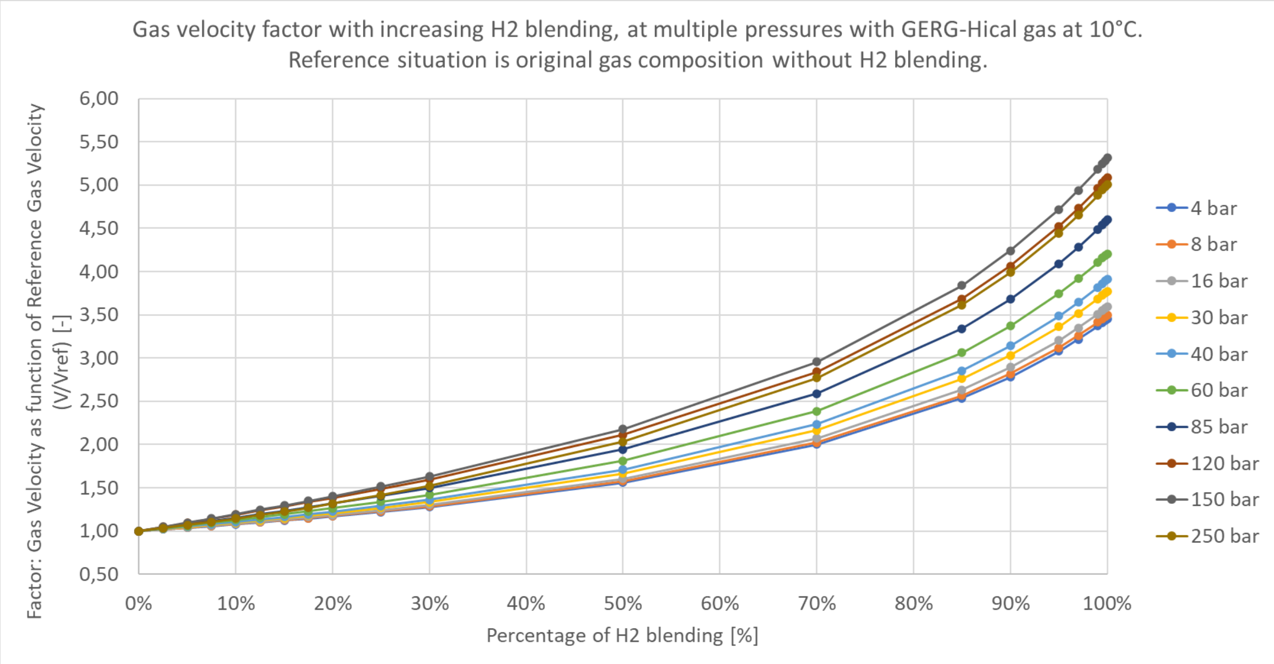

FIGURE 4. FLUID VELOCITY CHANGE AS A RATIO FOR GERG-HICAL GAS, AT DIFFERENT PRESSURES WHEN BLENDING HYDROGEN.

Regarding the speed of sound, results show that the introduction of hydrogen in natural gas increases the absolute speed of sound, with a more notorious effect at pressures above 120 bar. The Mach number, which is the ratio between the fluid velocity and the speed of sound, is compared at the different pressures and hydrogen concentrations. Generally, the Mach number increases with hydrogen blend percentages and it is important for flow-related integrity risks calculations.

After evaluating the dynamic viscosity, density and fluid velocity, the Reynolds number Re was calculated and compared for the different pressures and hydrogen concentrations. In general, Re varies within the ratio 0.5-2.0; which suggests that hydrogen blending does not have a significant influence on the type of flow.

Another interesting result is the variation of the dynamic pressure ratio. This value depends on density (which decreases with more hydrogen) and the required fluid velocity (which increases with more hydrogen) to maintain the same energy capacity in this case. Since the level of variation differs depending on the percentage of hydrogen blended, it is observed that the increase in required velocities dominates at lower hydrogen percentages, while the decrease in density becomes dominant at higher hydrogen percentages. For that reason, the dynamic pressure ratio increases up to around 85% hydrogen, and decreases between 85% and 100% hydrogen. The level of variation is higher for higher pressures.

Finally, contrary to volumetric properties, the mass flow required decreases as the percentage of hydrogen increases. This is explained by the fact that, even though the energy content decreases when adding hydrogen, the density decreases more strongly. Hence, the mass flow ratio decreases for all pressures, since the energy content per kilogram increases as the amount of hydrogen blended increases.

Energy capacity impact

Based on the equal energy scenario, the impact of pipeline capacity has been studied, along with pressure reduction systems, metering systems and heating systems. For a pipeline system, the Darcy-Weisbach equation is employed to calculate the pressure drop. Considering that the dynamic pressure increases when blending hydrogen, the pressure drop over the pipeline consequently increases, resulting in a reduction of pipeline transport capacity. Once again, for the various pressures considered, the higher the percentage of hydrogen blended, the higher the pressure reduction and therefore the energy capacity reduction. Furthermore, the variation of the friction factor seems to play a minor role in the calculations of flow capacity of pipelines.

Pressure Reduction Stations (PRS) are important components of the gas network. Pressure reduction devices (e.g., valves, bends) are characterized similarly to pipelines, meaning the pressure loss is proportional to density times velocity. Nevertheless, pressure control valves are characterized differently as these have their own valve capacity characteristics to consider (e.g., geometry, valve coefficient, Reynolds correction). In this analysis, a pragmatic approach was followed by a single discharge coefficient that takes into account these specific factors; then calculating and comparing the isentropic expansion coefficient for various pressures and hydrogen percentages. The energy flow capacity ratio (i.e., capacity restriction) was calculated at various pressures and hydrogen concentrations to better visualize the change in the valve capacity compared to natural gas. The capacity reduction is larger at higher pressures and the increase in speed-of-sound does not fully compensate the required increase in velocity.

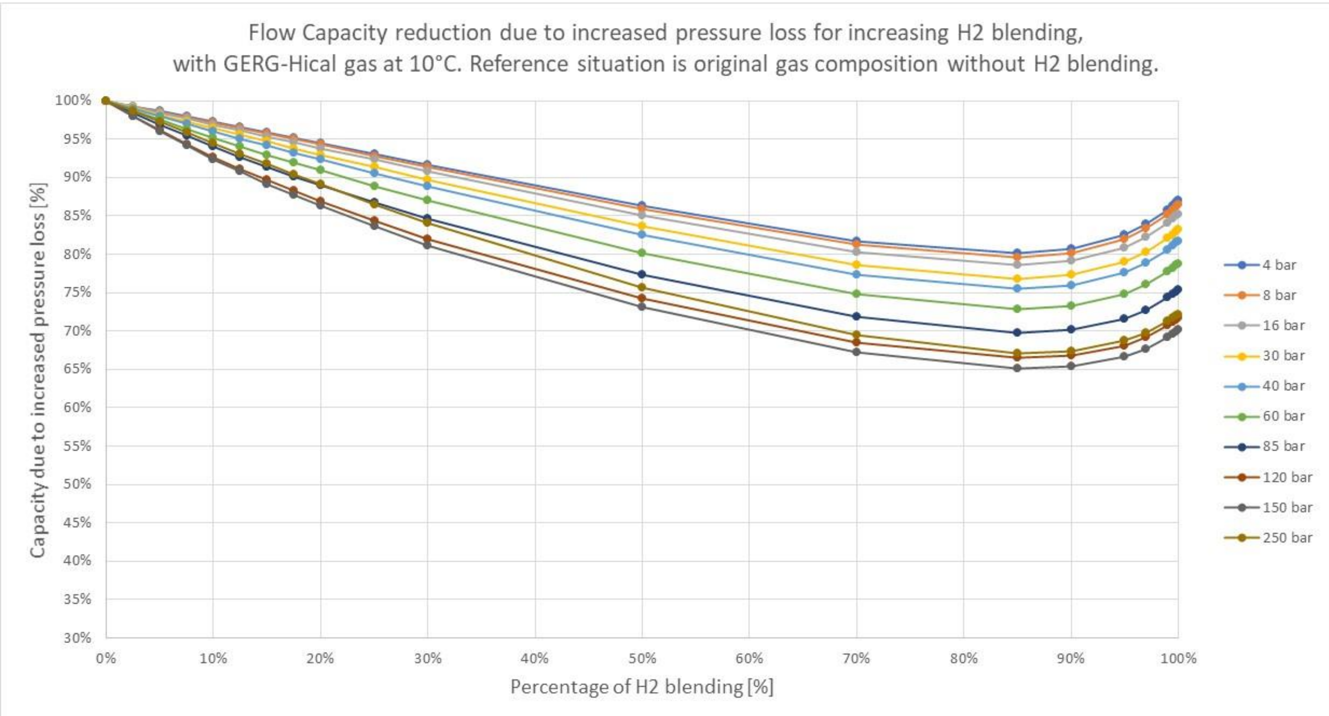

FIGURE 5 POTENTIAL LACK OF PIPELINE CAPACITY, CAUSED BY INCREASED PRESSURE DROPS DUE TO DYNAMIC PRESSURE INCREASE (GERG-HICAL CASE).

In metering stations, different types of volumetric flow meters are typically used along with pressure and temperature transmitters. Moreover, metering lines are used to be able to handle a maximum volumetric flow rate. As higher velocities are needed when transporting hydrogen, the impact on the change of required volume capacity of metering stations is evident. On the other hand, for geometric based measurements, the higher pressure differential observed when blending hydrogen results in pressure drops that also arise capacity problems and should be considered when selecting the pressure transmitter or orifice plate.

In PRS, heating systems are also employed to countereffect the Joule Thompson effect that is common in natural gas as temperature drops. In this case, the outlet temperature was calculated based on the isenthalpic expansion and subsequently the Joule Thompson coefficient. The heat transferred from the steel towards the fluid was compared between natural gas and hydrogen, based on thermal conductivity, which is higher for hydrogen. Furthermore, convection was also considered in the heat transfer model to take into account fluid motion; but the overall effect of hydrogen on heat transfer capacity is not significant compared to natural gas, since less heat is required.

Flow related integrity risks

The impact of changes to the gas properties when transporting hydrogen on pipelines has been investigated on different potential vibration sources, as this is a critical aspect to avoid flow-related excessive vibration. Following the EIG guidelines, a qualitative assessment of the Likelihood of Failure (LOF) was used. On a quantitative basis, the change in kinetic energy should be re-evaluated when blending hydrogen, the possibility of choked flow must be evaluated as well as the presence of intrusive elements.

Concerning Flow Induced Pulsations (FIP), an analysis was carried out, particularly on the side branch of a line, where stagnant flow instability may form vortices and subsequent pressure fluctuations that, when accumulated, could result in vibrations leading to pipework damage. Following the EIG technical module for flow induced pulsation, the critical diameter, the Strouhal Number side branch and the frequency factor comparing the vortex frequency with the eigenfrequency. They were all calculated for the various pressure values of the study at the different hydrogen blending percentages previously used. Results show that the risk of vibration caused by pulsations increases with increased hydrogen blending percentage.

Considering the higher velocities when transporting hydrogen in pipelines, Flow Induced Turbulence (FIT) could create vibrations and consequent fatigue/failure. Based on the corresponding technical module of the EIG, the likelihood of FIT was calculated with an LOF equation that depends on gas viscosity, stiffness of the pipe, kinetic energy of the flow and a geometry factor. Results show the LOF increases when blending hydrogen, but then decreases at higher percentages of hydrogen as gas viscosity decreases.

Acoustic Induced Vibrations (AIV) come from high frequency acoustic excitation that can be experienced downstream of pressure reducing devices. The corresponding technical module in the EIG is based on the calculation of the sound power of the source at each weld downstream and a simplified fatigue assessment. Blending hydrogen results in an increase of the sound power level downstream the device.

Flow Induced Vibrations of intrusive elements (FIV) were also calculated following EIG, which depend on the Strouhal Number intrusive element and the vortex shedding frequency versus eigenfrequency. Increased velocities to meet energy capacity demand when blending hydrogen result in an increase of the risk of vibration occurring.

Finally, the risk of erosion caused by small particles at significant fluid velocities was analysed, since this could lead to a potential pipe wall damage. Using a maximum sand/particle rate criterium, the impact on the limit in allowed particle rate decreases with an increasing content of hydrogen. Furthermore, the erosion rates were also calculated for bends by using a particle size correction function and geometry factors. In general, the risk of erosion increases for all the pressure values evaluated as the percentage of hydrogen blended increases; nevertheless, since transportation pipelines are well filtered during common maintenance procedures, it should be common practice to be below the allowed particle rate limit for erosion.

Some conclusions

It is concluded that the general effect of blending hydrogen in existing natural gas networks results in an energy capacity decrease (pressure drop), for which it is necessary to increase the new fluid velocity. As long as the natural gas network is not used beyond 90% of its maximum capacity limit, blending up to 20% hydrogen poses no problems in terms of velocity increase and corresponding pressure drop.

For higher percentages of hydrogen in blends, the required fluid velocity needs to be increased to transport similar amount of energy. Even though the density decreases, the pressure drop across the pipelines is larger. It may still be acceptable, but in some conditions of peak energy demand, or in specific components of the network such as pressure reduction stations it may cause integrity or capacity problems; it is recommended to analyse each part of the network in order to determine which pipeline sections are closer to their capacity limit and the presence of network components that are more susceptible to the increased hydrogen velocities. Nevertheless, 95%-100% hydrogen in blends generally have a lower impact on capacity and integrity of the network, compared to 50%-98% hydrogen in blends.

In summary, blending 20% hydrogen, or occasionally 30% hydrogen with natural gas has no major impact on the capacity and flow related integrity risk of the existing network. If higher concentrations of hydrogen are desired, based on the various impacts studied and the changes in the fluid properties, it is advised to switch to 98%-100% hydrogen, when the density decrease has been fully deployed.

Two velocity-related integrity effects have been identified as requiring closer attention. First, the risk of vibration of intrusive elements, since due to the higher hydrogen velocities, the integrity risk for fittings like thermowells increases, considering also the increase in the vortex shedding frequency. Secondly, the risk of erosion with increased velocity may pose higher erosion potential at pipe joints, bends and elbows due to the presence of particles. It is recommended to evaluate aspects such as the presence of dust in the repurposed pipe, flow evaluation to assess pick-up velocity of pipeline debris and in general maintaining or reinforcing operational practices.

If the limit in the capacity is reached, a re-evaluation of the flow induced vibration is recommended. Intrusive elements such as thermowells can become an integrity risk due to the higher flow velocities in hydrogen (blend) operation Also, increasing velocities when transporting hydrogen poses a higher risk of erosion caused by small particles. Nonetheless, appropriate cleaning and maintenance actions is required to significantly mitigate this risk.

For pressure control lines and (sonic) valves, the capacity reduction is determined by the speed-of-sound and this capacity reduction is lower compared to the pipe and manifold static elements, except at higher pressures (> 150 bar). For metering lines, , an expansion of the system capacity is required due to the higher velocities. One solution could be to place extra metering lines or to increase the diameter of the metering lines.

The heat transfer capacity is hardly affected by the increased velocities in the blending. No capacity issues are expected in heating systems during blending of hydrogen. In fact, at 100% hydrogen, no heating is needed.

The GERG project: Energy capacity related effects of repurposing natural gas pipelines for hydrogen or hydrogen blends[11] that was summarised here, is a valuable piece of work that contributes to the documentation of the impact of using an existing natural gas transmission network for transporting hydrogen with the same energy capacity as for natural gas. The quantitative evaluations are specific to the industry conditions recommended by project participants. For instance, at 10° C, for specific pressure values and various percentages of hydrogen, for the 3 reference gases selected, particularly for the equal energy transmission scenario (E-EQ). Other scenarios and conditions and models could be studied to validate the trends in the results.

More detailed analysis may still be required after implementing some of the qualitative evaluations described here, on a case-by-case basis. For example, the increase in risk erosion when adding hydrogen needs more careful examination, especially when the reference natural gas has a high calorific value, meaning a much larger increase in velocity is required to compensate the energy content when introducing hydrogen. Moreover, next to the analysis of flow related integrity risks in this work, the impact on the material properties due to hydrogen embrittlement shall be considered in future work.

We thank the DNV team for delivering this essential project and the partners Gasunie, Enagas, Fluxys, GRTgaz, Storengy, National Grid and DGC for making this project successful within the GERG framework.

[11] GERG., 2022. Energy capacity related effects of repurposing natural gas pipelines for hydrogen or hydrogen blends (Report)