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Assessing the Feasibility of Repurposing the Existing Natural Gas Pipelines for Hydrogen Transport – A Comprehensive Review

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Abstract

In a bid to investigate the optimum transportation method for the offshore wind produced hydrogen (H_2) and assess the feasibility of repurposing the existing oil and gas infrastructure for H2 transmission; this paper assesses the existing H2 transportation methods with a comprehensive review of the H2 impact on the existing natural gas pipelines infrastructure. To establish the possibility of repurposing the existing natural gas (NG) pipelines for H2 gas transport, this paper reviews the influential technical measures; composition, pressure, temperature, volumetric energy density, density, and pressure drop to assess whether the characteristics of hydrogen gas are compatible with the natural gas pipeline infrastructure. Based on these reviews, it was found that the current NG pipelines pressure exacerbates the H2 embrittlement and for the existing NG pipelines to be repurposed, the operating pressure should be reduced, and the pipeline material should be revised. It was found that higher strength steels can be re-used with major modifications, or the pipeline should be constructed from X52 material grade or below. Nevertheless, the fitness of the existing NG pipelines for H2 transmission should be assessed on a case-by-case basis and other factors such as erosion, leakage, monitoring and rigorous assessment of welds and joints should also be considered.

Keywords: hydrogen (H2); H2 gas transmission; gas pipelines; natural gas transmission; pipelines repurposing; pipelines operating parameters; pipeline material; transmission costs

1. Introduction

Hydrogen is viewed as a practical solution to completely decarbonise the global economy and is therefore gaining momentum. Hydrogen is very important because it leaves zero-carbon footprint when deployed for energy consumption [1]. The last decade saw the emergence of fossil fuel as the dominant source of our energy needs [2]. Currently, increasing population, urbanization, and economy are placing increased demands on energy needs driving the implementation of renewable energy sources like wind [3]. Climate is another factor driving the switch to cleaner alternatives [4]. To support the increased integration of renewables, like offshore wind, the utilisation of energy storage solutions like the offshore production of green H2 from the excess in wind energy becomes essential [5]. Electrolysers are used to generate H2 from the excess in offshore wind energy [6]; and this H2 can then be transported using pipelines. Therefore, an opportunity exists in deploying the existing oil and gas offshore infrastructure for the transportation of this offshore generated H2. It has been found that repurposing an existing pipeline to transport hydrogen instead of constructing an entirely new pipeline is considerably cheaper [7]. Jens et al (2021) [8] estimated that the cost to repurpose an existing pipeline to transmit hydrogen is approximately €0.2 to €0.6 M/km compared to around €1.4 to €3.4 M/km to build a new pipeline [7,8].

Currently, few hydrogen pipelines exist around the world. In Belgium, there is an 80km long pipeline with Internal Diameter (ID) of 5.9-inch which operates at 100 Barg [9]. In England, there is a 16km long pipeline which operates at 50 Barg. Another example is a 220km long hydrogen pipeline in Germany that operates at 20Bar and has linked Dusseldorf and Recklinghausen for 60 years. It has an internal diameter of 3.9-inch to 11.8-inch [9] and transports 1,000,000m3 of H_2 per year. Other examples include a 550km long pipeline in France with Internal Diameter (ID) of 100mm transporting 2,000,000m3 of H2 yearly; a 100km H_2 pipeline laid in Texas, and hydrogen pipelines covering several kilometres in Iowa, Louisiana and Alberta, Canada [9].

Considering that the oil and gas production is on the decline and in due course will be replaced by offshore renewables such as wind, the transmission of the hydrogen gas generated from offshore renewable systems (like wind) using the stranded oil and gas infrastructure presents a promising opportunity.

This paper investigates the optimal methods of offshore hydrogen transportation and assesses the viability of reusing the existing natural gas pipelines infrastructure for H_2 transport. A thorough literature review was conducted and all H_2 transmission options were evaluated based on their pros and cons. Based on this, H2 transport in pipelines was identified as the optimal solution for the transportation of H2 over short to medium distances.

The feasibility of reusing the existing NG pipelines for the transport of hydrogen gas was also reviewed in this paper using technical measures like composition, pressure, temperature, pressure drop, volumetric energy density and operating density.

While literature is replete with studies exploring the feasibility of transporting hydrogen as a blend with Natural Gas in natural gas pipelines, the transport of pure hydrogen gas has been understudied. There is a dearth of comprehensive reviews on the impact of technical measures on the existing NG pipelines when repurposed for the transportation of pure hydrogen gas produced from offshore wind farms. This paper addresses these gaps through a comprehensive review of the impact of influential technical measures on the existing natural gas pipeline when repurposed to transport the hydrogen gas produced from offshore wind farms.

2. Methodology

As can be seen in figure 1, a comprehensive review was first completed in this paper to assess all the viable hydrogen transport methods and accordingly identify the optimum transport method. Twenty-three reputable publications were used to carry out this assessment, from which pipelines were identified as the optimum method for the transport of hydrogen gas.

The literature review was then further synthesized to assess the impact of the H2 gas operating characteristics on the existing natural gas pipeline infrastructure in order to examine the feasibility of re-using the existing natural gas pipelines for the transport of hydrogen gas.

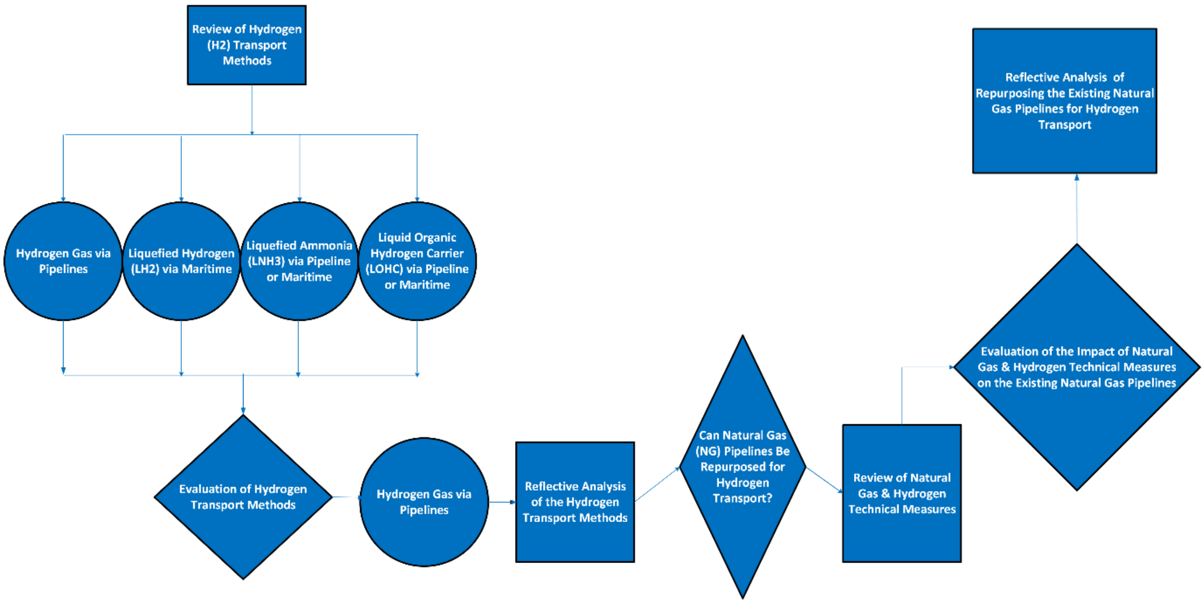

Figure 1. Methodology.

3. Review of Existing Hydrogen Transport Methods

3.1. Hydrogen Gas Transport

As the lightest molecule, the density of H_2 is very small. The low density (0.08375 kg/m3) and the low volumetric density of gaseous H2 means that it is challenging to transport gaseous H_2 in large volumes [10–12]. It is imperative to investigate other options to transport H_2. To boost the gaseous H_2 density and the transportation challenge, compression of gaseous H2 and transportation via pipelines is an option that has been suggested.

H_2 is not a toxic gas [10] which doesn't generate much radiation energy [13,14] when it burns. However, with a Molecular Weight of 2.016 g/mol [15] and density of 0.08375 kg/m^3 it's small and very light [9,13]. The small size, lightness and flammability make its application challenging [10,15,18]. Because of the lightness, it is more easily leak through joints, cracks, and seals of containment than other gases [9,13]. Attention should be paid to the mechanical joints of H_2 transmission lines [14]. Because of this, new valves, fittings, seals, and gaskets [9] should be used for hydrogen transmission lines.

H2 has wide flammability range which is between 4% and 75% [10]. However, its high flame speed (346 cm/s), low flammability (4%) and low ignition energy (0.02 MJ) [10,16] means it is explosive [10]. Nonetheless, the impact of any potential fire is mitigated by its low radiation energy and its lightness [10]. On exposure, the lightness enables it to rapidly diffuse through air [10].

H_2 embrittlement occurs when H_2 diffuses on metal surfaces causing the degradation of its mechanical properties [13,15–17]. Cracks created by embrittled metals can cause loss of containment and create a flammable atmosphere which can heighten the risk of explosion. Because of embrittlement concerns H_2 transport pipelines are typically operated between 30 Bar and 60 Bar [18].

There is a significant industrial experience of using H_2, including its deployment in purpose-built distribution lines with existing site-specific safety practices [10]. In green H_2 production, an electrolyser is used to generate H2 from an offshore wind farm [6]. This can then be compressed and transported using pipelines. At 100 Bar and 20 °C, the density of compressed gas is ≈ 7.8 kg/m^3 [18] which is an improvement on the density and the transport capacity of uncompressed gaseous H_2.

A key feature of transmission by pipelines is the uninterrupted supply of H2 gas to meet energy demand. It is believed that this is the most economical choice for the long-distance transportation of hydrogen [1]. However, a major handicap is the insufficient pipeline infrastructure, with just 5,000km of H2 dedicated lines connecting Asia, Europe, and North America, in contrast to the 3 million km for NG [15]. Some of the examples given by Gondal [9] includes an 80km pipeline in Belgium with Internal Diameter (ID) of 5.9inch and operating at 100Bar: a 16km hydrogen pipeline in England, operating at 50Bar, and a 220km H_2 pipelines in Germany, with ID of 3.9inch to 11.8inch, operating at 20Bar.

The low volumetric energy density of Hydrogen (10.8MJ/Sm^3) presents a transportation challenge [19]. For natural gas, this is 36.4MJ/Sm^3 [20]. To achieve equivalent energy output, more volumetric flowrates of H2 must be compressed [21] in bigger diameter pipelines [10]. The high energy density (120.1MJ/Kg) [10] makes H_2 compression and transport through a pipeline an attractive proposition.

Based on the literature, this is a simple method of transmitting H_2 that guarantees continuous H_2 supply to end users. Its end use includes electricity generation, drive automobiles and industry or heat home and business appliances [22]. If this option is utilized, the delivery of non-toxic gas which is dense in energy can be achieved. This is consistent with decarbonisation. The high energy density and the continuous supply should compensate for the relatively low volumetric energy and transport densities.

Embrittlement which increases degradation at higher pressures and concentration is concerning. There are other safety constraints that can be managed. H2 is explosive. However, its ease of diffusion and low radiation energy inherently mitigates this concern.

3.2. Liquefied Hydrogen (LH2) Transport

The low volumetric energy density of gaseous H_2 [21] can create transport issues [12], which can be addressed by liquefying H_2. Through liquefaction the density of H2 can be increased to 71.1 kgH_2/m^3 and more volume can be transported [11].

Because of the higher density, LH2 has good prospects [12,23]. The density (71.1kgH_2/m^3) is superior to gaseous H2 (0.08375 kg/m^3). Like gaseous H_2, the gravimetric energy density or the energy per unit mass (120.1MJ/Kg) of LH_2 is high [11]. Thus, it is very rich in energy. However, as the boiling point (BP) of H_2 (-253°C) is extremely low, the cooling process to produce LH_2 requires a lot of energy contained [11,23]. 30 to 44.7% of the energy in H_2 is lost to cooling [11,24,25].

Additional energy losses [11,23] and costs [10,15] are required to conserve the low temperature required during transport in cryogenic vessels [24,25]. Due to these, LH_2 is not deemed efficient for transporting H2 [15,23]. Also, in transit, LH_2 can be subjected to thermodynamic losses or Boil off Gas (BOG) which can impact recovery [11]. BOG is estimated as ≈ 0.52 vol% per day [25]. However, at the destination, evaporation at ambient conditions releases gaseous H_2 and for this, no energy is lost [11].

3.3. Liquefied Ammonia (NH_3) Transport

Ammonia has long been utilised as a refrigerant and as feedstocks to produce fertilisers and explosive; and customarily, it is shipped in ocean vessels [10]. Furthermore, ammonia contains no carbon molecule, making it a potential candidate for transporting H_2 [26].

Liquid ammonia is transported at a low pressure of 1 Bar and below –33.34°C considered favourable conditions [23]. Furthermore, ammonia has high auto ignition levels (15 to 28 vol%), which implies that it will not speedily ignite if an ignition source is nearby. However, ammonia is highly toxic and corrosive - its application has health and safety concerns. Its handling and usage are restricted to competent operating practitioners [10]. Also, ammonia can cause air pollution through acidification if it escapes when partially combusted [10].

Ammonia has a Molecular Weight of 17.031 g/mol [11]. It requires liquefaction at -33 °C [19] to be converted to its denser liquid form for long distance transport [3] and this liquefaction temperature can be readily achieved [10].

Liquefied ammonia is characterised by high volumetric energy density (14.4Wh/L) [3]. Because of this, the volume of H2 that ammonia can transport is high [10]. Furthermore, the high volumetric H2 content (121kg/m3) and density (686kg/m^3) of liquid ammonia [11,23] are good indication of its capacity to transport H_2 in large volumes [23].

The BP of ammonia (-33.34°C) is relatively high, meaning that it's easily liquefied and conserved in liquid form during transport [11]. Because of this, its BOG of 0.024% to 0.1% per day during transport is moderate, meaning that product recovery will be sufficient [11,25]. Nevertheless, the energy required for dehydrogenation (>30.67 MJ/kg) is massive [11]. Also, comparatively, the gravimetric energy density (21.18 – 22.5MJ/Kg) is low. To put this in context, it's 120MJ/kg for LH2.

3.4. Liquid Organic Hydrogen Carriers (LOHCs)

LOHCs was first investigated by Japanese researchers conducting studies on Benzene/Cyclohexane systems in the 1980s [27]. Fundamentally, LOHCs are organic molecules that can chemically attach H2 to their structure and are of similar characteristics [28].

Methylcyclohexane (MCH), an LOHC derived from toxic Toluene [10] is the best known LOHC [11]. Generally used in the production of organic chemicals, it is a colourless liquid with an odour like Benzene [29]. Dibenzyltoluene and Benzyltoluene are other examples of LOHCs [10,30]. However, this report is based on MCH, the most popular LOHCs.

MCH is transported at ambient conditions (1Bar & 20 to 25°C) and is therefore stable and safe for transport [15]. However, MCH is flammable. It has low range of ignition in air (1.2 to 6.7vol%) [11], however, any risk of leakage and fire is significantly reduced due to its stability [28]. Furthermore, MCH is a liquid and less harmful compared to gases which can be inhaled. Thus, its transmission should not cause serious safety issue if adequate measures are installed [10].

At 101°C, the BP of MCH is high, therefore there is no liquefaction required for transport and thus no energy costs incurred [15]. However, its gravimetric (7.35MJ/Kg) and volumetric (5.66Wh/L) energy densities are low. In addition, its gravimetric (6.1%) and volumetric H2 (47.1%) content are also low. Because of these, if used as an H_2 carrier, LOCH will deliver small amount of H_2 [11].

At the destination, significant amount of energy (>43.4MJ/kg) is required for dehydrogenation [11]. Energy consumed for this process is ≈30-40% of the energy stored in the H_2 [31]. Also, following dehydrogenation, residual LOHC molecules must be recycled for hydrogenation [10]. LOHC molecules are costly and should be re-used, however, recycling unloaded LOHCs is complex and costly [10].

3.5. Methanol Transport

Methanol (CH_3OH) is an H_2 carrier viewed as having the prospect of transporting H_2 [34]. It is rich in H_2 and can be reformed to H_2 [24]. However, when methanol decomposes to release Gaseous H_2, CO_2 and CO are produced [11,23]. CO which is very poisonous is produced [11,23]. Therefore, the use of methanol for H2 transport will lead to environmental pollution [10,23]. Based on this, methanol as a hydrogen transport option is not discussed further in this paper.

4. Evaluation of the Hydrogen Transport Methods

To enable the evaluation of the different H2 transport methods, Table 1 has been developed to summarizes the key attributes of the reviewed Hydrogen transport options.

Table 1. Key Characteristics of the Different H2 Transport Methods [10,11,15,18,21,23].

	H_2 Gas	**LH_2**	**NH_3**	**LOHC (MCH)**
Molecular Weight (Wt.), g/mol	2.016	2.016	17.031	98.186
Density in normal conditions, Kg/m3	0.08375	0.08375	0.73	866.9
Melting point, C	-259.16	-259.16	-77.73	-126.3

Explosive limit in air, vol%	4 to 75	4 to 75	15 to 28	1.2 to 6.7
Flame speed, cm/s	346	346	-	-
Liquefaction energy, MJ/Kg	N/A	15.1 to 57	> 6.73	N/A
Transport pressure, Bar	100	1.013	1.013	1.013
Transport temp, C	20	-252.87	-33.34	20 to 25
Density in transport conditions, kg/m^3	7.8	71.1	686	866.9
BOG, % day	N/A	0.06 to 0.4	0.024 to 0.1	0.00416 to 0.065
Gravimetric energy density, MJ/Kg	120	120	21.18 to 22.5	7.35
Gravimetric H_2 content %	100	100	17.8	6.1
Volumetric energy density, MJ/Nm3 [Wh/L]	13 [8.49]	13 [8.49]	[12.92 to 14.4]	[5.66]
Volumetric H2 content kg/m^3	100	70.8	121	47.1
Dehydrogenation energy (MJ/Kg)	N/A	-	30.67	> 43.4

The reviewed H2 transport methods were then analysed to evaluate the Pros and Cons of each method, and Table 2 was developed to demonstrate this evaluation.

Table 2. Evaluation of the H_2 Transport Methods.

H2 Transport Methods	Pros	Cons
H_2 Gas in Pipelines	• Very clean, non-toxic fuel that when it burns no GHG is produced. • Low radiation energy and diffuse easily. • Very rich in hydrogen-energy. It has very high energy density. • Requires no liquefaction, and therefore no associated energy cost. • No requirement for dehydrogenation and hence, no energy cost.	• Low auto ignition temperature and high flame speed and therefore very explosive. • Low volumetric energy and transport density. • Burns in air with invisible flames and thus may not be quickly detected

	- Boil off gas (BOG) is non-existent. - Continuous delivery of H_2 - Transport density can be increased by compression	
LH$_2$	- LH2 is a very clean, non-toxic fuel. - No energy consumption required to release gaseous H_2 at the destination. - It is very rich in Hydrogen energy, like compressed H_2.	- Low auto ignition temperature and high flame speed and therefore very explosive. - Extremely energy intensive and wastes too much energy. Cooling consumes 30 to 36% of energy contained in H_2. - May require significant investment due to the low temperature conservation requirement. - Significant gas boil-off. - Low volumetric energy and storage densities.
Liquid Ammonia	- High auto ignition temperature and less explosive than H_2. - Does not produce CO_2, a GHG when oxidized. - High volumetric energy and transport density. It will deliver high volume of H_2. - Boiling Point is -33.34°C. Its liquefaction, storage, and conservation in liquid state demands less energy than LH_2. - Transportation is at ambient pressure. - Cooling requirement of < -33.34°C can be readily achieved.	- Un-combusted ammonia could cause pollution via acidification. - It is highly toxic and corrosive. - It is not rich in hydrogen-energy. The gravimetric energy density is low. - Some gas boils off. - Significant amount of energy is required for dehydrogenation.
LOHC (MCH)	- LOHCs, including MCH are stored and transported at ambient pressure	- LOHC (MCH) is very flammable and has serious potential to cause fire.

	conditions and are therefore stable and safe to transport. • MCH is a liquid and less harmful than gases which can be inhaled. • No liquefaction required, and therefore no associated energy cost. • It's stable and a liquid. Pipelines and maritime can be used for transport.	• LOHCs, including MCH have the least gravimetric and volumetric energy density. Also, it has low volumetric H2 content. It will deliver low quantity of H_2. • Requires significant amounts of energy to release gaseous H_2. • Complex due to requirements to recycle unloaded carriers for hydrogenation, and therefore, may not be cost-effective.

Following the detailed literature review and the analysis of the identified hydrogen transport methods, as summarised in Table 2, the transport of hydrogen as gas via pipelines has been determined as the optimum option as it offers the highest benefits with minimum drawbacks. The high energy density and the continuous supply characteristic of this option make it the most viable choice. It is also cost efficient as it requires no liquefaction nor dehydrogenation before utilisation, thus eliminating the associated energy costs.

4.1. Reflective Analysis on Hydrogen Transport Methods

Gaseous H_2 is viewed as a viable solution to decarbonise and realise net zero emission [3,10,15]. However, as reviewed in this work (Table 2), H2 gas has certain characteristics that can compromise the operational safety of the transmission pipelines made of steel materials. Gaseous H_2 is very volatile; it is very light and has low volumetric density, and because of this, it is difficult to transport it in large volumes. Therefore, it is necessary to assess all the H2 transport options. The assessed options included transporting H2 as gas via Pipelines, as Liquefied H_2 via maritime, as Liquid Ammonia via pipelines or maritime, as LOHCs via pipelines or maritime and as Methanol via pipelines or maritime. After a detailed review and analysis of the pros and cons of each option as summarised in table 2, it has been found that the transport of H_2 as gas via pipelines is the optimum option for hydrogen transport, particularly over short to medium distances, and where existing NG pipelines can be utilised to transport the H_2. The high energy density characteristic of this option and the continuous supply attribute compensate for its relatively low volumetric energy density attribute. Although, H_2 is explosive, its ease of diffusion and low radiation energy is a mitigation.

The LH_2 transport method is unattractive due to its extremely low cryogenic temperature requirements. While LH_2 transport has high gravimetric energy density like the H_2 gas transport in pipelines and an even higher transport density; the extremely low cryogenic temperature required for its transport and the excessive boil off means that this option is very unattractive

Liquid ammonia shipping offers the best option for the transport of H2 over long distances as it is rare to find pipelines existing across continents, and it is un-economical to build new H2 gas transport pipelines for such distances. Liquid ammonia additionally offers good transport qualities (volumetric energy density, volumetric H2 content and gravimetric energy density) and can be transported at ambient pressure and temperature of -33.34°C that can be readily achieved. However, the excessive energy required for dehydrogenation is a major constraint for this method of H_2 transport.

The stability of the Liquid Organic Hydrogen Carriers (LOHCs) method at ambient conditions means that they can safely transport H_2 via pipelines or maritime. However, this method is unattractive due to the excessive energy required for the dehydrogenation and the need to recycle unloaded molecules. Furthermore, the poor transport qualities (volumetric energy density, volumetric H2 content and gravimetric energy density) of this transport method means that if it is adopted, it will deliver very poor quantity H_2.

The Methanol transport option is unattractive because its decomposition releases poisonous CO and CO2. Its technical and safety characteristics was not covered.

4.2. Review of the Existing Natural Gas (NG) Infrastructure

The transport of Hydrogen gas in pipelines was identified in the previous section as the optimum method for transporting hydrogen in large quantities particularly over short to medium distances where the existing NG pipelines can be utilised. In this section, the suitability of the existing Oil & Gas infrastructure will be assessed with a focus on the existing NG pipelines.

The Natural Gas Infrastructure

Figure 2 demonstrates a simplified schematic of a NG transmission system. A typical NG infrastructure consists of pipelines, compression stations [9,21], city gate stations and metering stations that can be installed at intervals on the transmission lines to enable the pipeline operators to monitor and measure the NG in the pipeline and in storage facilities [32].

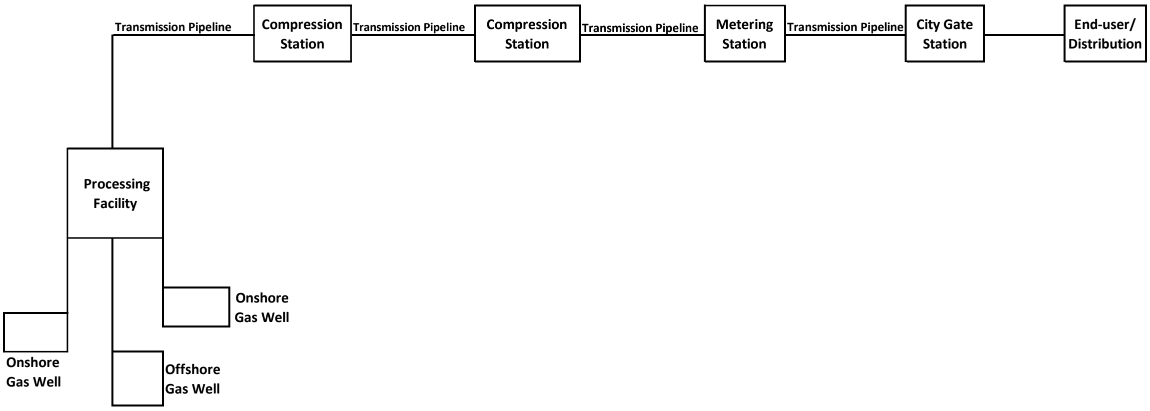

Figure 2. Natural gas transmission system.

The Natural Gas (NG) transmission pipelines typically range between 6 and 48 inch in diameter to transport gas at operating pressures between 10 to 120 Bar over long distances and 0.5-inch diameter pipelines are used in the gathering and distribution systems [19,32]. The gas travels through the pipelines when there is difference in pressure (DP) between two points in a pipeline system. The flow of NG, which must be adequate to meet energy demand, is dictated by the DP in the pipeline.

As NG must maintain pressure while travelling through transmissions lines, compressor stations are used to maintain pressures in transmission lines and are usually installed at intervals of 64.4km to 161km [32]. Metering stations are installed at regular intervals on the transmission lines to enable the pipeline operators and gas distribution companies monitor and measure the natural gas flowrates [32]. City gate stations are used to receive the NG from the transmission line before feeding it to the distribution systems. Primarily, the city gate will meter the gas from the transmission pipelines and reduce the pressure to what the distribution system can accept [32].

5. Repurposing the Existing NG Pipelines for Hydrogen Transport

In this section, the feasibility of reusing the existing natural gas pipeline infrastructure to transport hydrogen is reviewed and evaluated. The material of the NG pipeline is firstly assessed then the impact of influential technical measures such as gas composition, operating pressure and temperature, volumetric energy density, operating density, and pressure drop on the existing NG pipelines are assessed.

5.1. Review of Technical Measures

To establish the possibility of reusing the NG infrastructure for H2 transport, the material of the NG pipeline is firstly assessed followed by an assessment of the effects of technical measures such as the gas composition, operating pressure, operating temperature, volumetric energy density, operating density, and the pressure drop, on the safe and efficient operation of the gas pipeline.

5.1.1. Assessing the Pipeline Materials

Due to the NG high pressures involved [9], most NG pipelines are made from carbon steel [9] or stainless steel [19]. Material grades such as X52, X56, X60, X65, X70 and X80 which are high-strength steels are typically employed for NG pipelines [33,34]. While high-strength steels such as X52, X56 and X60 have a maximum operating pressure (MOP) of 207 Bar, X65, X70 and X80 have a maximum operating pressure of 103Bar [34]. High strength steels like X100 and X120 material grades are still under research and development, and their application in major projects is still challenging because the very high strength of these material grades makes them very prone to hydrogen induced stress corrosion-cracking and failure [34]. Common steel grades for Natural Gas distribution lines [19] are material grades A, B, X42 and X46 [33,34]. Materials grades A, B, and X42 have a maximum operating pressure (MOP) of 207Bar [34].

Currently, polyethylene (PE) materials are more common in the NG distribution pipelines [9]. PE pipes are now used in lieu of old iron and steel pipes [33]. As per the American Water Works Association, PE material is typically rated for just 17.5 Bar [35], with no evidence to suggest that they are prone to hydrogen embrittlement [36]. From a safety and economic perspective, PE is acceptable as a pipeline material to transport hydrogen [18].

The existing H_2 transmission pipelines are operated between 30 Bar to 60 Bar utilising lower strength steels which are usually API 5L X42 or below [18]. According to Mohitpour et al [18], at these operating conditions, little to no failures have been experienced [18]. In addition to this, according to Khan, M.A., Young, C. and Layzell, to contain the threat of H2 embrittlement, under normal operating conditions, low strength materials grades A, B, X42 and X46 are employed for H2 pipelines [19]. Furthermore, the American Society of Mechanical Engineers (ASME) [37] declares that API grades below X42 and X52 are less affected by H_2 embrittlement [16] and are approved for hydrogen pipelines.

Therefore, based on the undertaken review, it can be concluded that using NG pipelines that are made of materials grades X52 and below to transport H_2 at reduced pressures of 30 Bar to 60 Bar will carry the threat of H_2 embrittlement [16,18,19].

Although it is economically more beneficial to use high-strength steel pipelines for hydrogen transport instead of low-strength steel because of its smaller pipe thickness [38], high-strength steels which are often used for NG transmission are more prone to H2 embrittlement [19].

Nonetheless, with major modifications, the existing NG pipelines constructed from higher strength steel grades can be utilised to transport pure H2. Degradation Inhibitors such as oxygen (O2), sulphur (IV) oxide (SO2), & carbon monoxide (CO) and Pipe in-Pipe technology can be used to modify the existing NG pipelines constructed from higher strength steels [39]. The Pipe in-Pipe technique can be used for the modification of the existing NG pipeline by inserting an inner pipeline of material that is not prone to hydrogen embrittlement to provide a physical barrier between the steel pipeline and the gaseous hydrogen being transported [39].

5.1.2. Gas Composition

To meet energy requirements, the NG flowing in the NG pipelines consists of roughly 87 to 96% methane (CH4) [33]. With methane being the main component of the NG [13], the typical composition of the NG flowing in NG pipelines [40] is given in table 3 [1]. NG whose primary component is methane has a high volumetric energy density (35.8 MJ/Sm^3) which is thrice the volumetric energy density of hydrogen (10.8 MJ/Sm^3) [19].

Table 3. Natural Gas Typical Composition [1].

Component	Mol Fraction (%)
Methane	93.76
Ethane	3.14
Propane	0.62
Butane	0.2
Pentane	0.07
Nitrogen	2.03
Carbon dioxide	0.18

Any change in the natural gas composition could create difficulties in the pipeline operation because this change can affect gas (mixture) properties such as density, dynamic viscosity, Joule Thomson coefficient, heat capacity, thermal conductivity, volumetric energy density, causing metering inaccuracy [40].

As a transitional measure, the UK is targeting 20 to 30% of hydrogen in a natural gas mixture [1]. As a permanent measure, it is expected that 100% of hydrogen can be transported through the existing high-pressure pipelines [1].

Hydrogen composition is a determining factor on the degree of pipeline degradation [17]. Some metal pipelines can be compromised and degraded on the prolonged exposure to hydrogen existing at high concentrations and pressures [1]. Generally, steels are more prone to embrittlement at H_2 concentrations greater than 30% [1]. For this reason, H2 can be transported in NG pipelines at reduced concentration if embrittlement is concerning [13].

H_2 embrittlement, which occurs when H2 diffuses on metal surfaces causing the degradation of its mechanical properties [13,15–17], can compromise the pipeline operational safety. Cracks created by embrittled metals can cause loss of containment and create a flammable atmosphere which can heighten the risk of explosion. Hydrogen embrittlement can be prevented by restricting the ingress of hydrogen into the lattice structure of the host pipeline material [1]. Rigorous assessment of the pipelines welds and joints can give indication of the likelihood of future H2 embrittlement and pipeline degradation [23].

5.1.3. Operating Pressure

There has been a steady rise in the operating pressure of natural gas pipelines through the years. Based on the undertaken reviews, the operating pressure of the NG transmission system ranges from 10 Bar to 138 bar [9,19,33,41] at 37.8°C to 48.9°C [33], whereas the maximum operating pressure of a pipeline transporting H_2 is 100Bar and at about 20°C. At this operating condition of 100 Bar and 20°C, the density of the compressed H2 gas is about 7.8 kg/m^3 [18].

To maintain the continuous supply of energy, the operating pressure of the pipeline needs to be increased above 100 bar to push more volumetric flow of hydrogen gas [40]; however, operating pipelines at increased pressure could adversely impact the integrity of the NG pipeline if it goes beyond its design pressure [40]. However, the impact of embrittlement is exacerbated by pressure [1,13,17,42]; consequently, H2 transport pipelines are typically operated between 30 Bar and 60 Bar [18].

5.1.4. Operating Temperature

Based on the undertaken review, the operating temperature of the natural gas pipeline ranges from -6.7°C to 60°C [9], whereas the normal operating temperature of the Hydrogen Pipeline is below +50°C [17].

Furthermore, based on the undertaken reviews, it has been found that when the pressure of the NG pipeline is reduced, temperature drops by 0.5°C for every 1 Bar reduction [9]; this phenom is called the Joule Thompson (J-T) effect [9,21]. This J-T effect can impact the NG pipeline materials and cause safety issues. Throttling NG from 80 Bar to 15 Bar causes the temperature to drop by 32.5°C, which is significant [9].

In NG transmission, the J–T effect can lead to serious shifts in temperature that can cause profound thermodynamic change in the NG pipelines infrastructure. The cooling effect can lead to the formation of hydrates that can plug valves or gas pipelines when water drop out of the wet hydrocarbons [1]. To avoid the formation of ice-like hydrates, which have pipeline safety implications, the NG pipeline is usually heat traced [9] to prevent hydrocarbon liquids from condensing in the pipeline [40].

However, in H_2 transmission, when pressure is reduced, H2 temperature increases by 0.035°C for every 1 Bar reduction [9,21]. Reducing the pressure of H_2 from 80 Bar down to 15 Bar causes a 2°C rise in temperature which does not have any safety implication [9,17,21] for the existing NG pipeline.

5.1.5. Volumetric Energy Density

NG has thrice the volumetric energy density (35.8 MJ/Sm^3) of Hydrogen (10.8 MJ/Sm^3) [19]. For Hydrogen to replace the natural gas in the existing NG infrastructure the volumetric flowrates of H_2 supplied to the end user must be increased [19] to meet the energy content requirements [9].

However, increasing the volumetric flowrate can cause the flow velocity to increase; therefore, the H2 flow velocity must be monitored to be kept below 20m/s (max) when flowing in the repurposed NG pipelines to prevent its internals from eroding.

Few mathematical relationships are used to relate the gas properties to its flowrate, the length of pipe, pipe diameter and the inlet and outlet pressures [53]. Some of these equations are the:

- General energy equation
- AGA equation
- Weymouth equation
- Panhandle A & B

Along with the gas laws, equation 1 [43] is the basic energy equation applied to study the performance of a gas pipeline. If the pressure at the inlet and outlet of a pipeline segment are known, the steady-state isothermal flowrate of the gas through the pipeline can be estimated [9].

$$Q \;=\; 38.77 \;(\frac{T_b}{P_b})\, \mathrm{E}\, \frac{\sqrt{1}}{f_f}\, [\frac{P_1^2 - P_2^2}{SL_m T_{avg} Z_{avg}}]^{0.5}\; D^{2.5} \tag{1}$$

Where:
Q = flowrate of gas, cubic feet per day at base conditions.
T_b = base absolute temperature, °R (ANSI 2530 specification: T_b = 520°R).
P_b = base absolute pressure, psia (ANSI 2530 specification: P_b = 14.73 psia)
E = pipeline efficiency factor (fraction).
F_f = Fanning friction factor
P_1 = inlet pressure, psia
P_2 = outlet pressure, psia
S = specific gravity of flowing gas (air = 1.0)
L_m = length of line, miles.
T_{avg} = average temperature, °R, [$T_{avg} = 1/2\ (T_{in} + T_{out})$]
Z_{avg} = average compressibility factor
D = internal diameter of pipe, feet

5.1.6. Operating Density

The operating density of NG is nine times that of hydrogen [17]. The high contrast between the density of natural gas (74.62 kg/m^3) and the density of hydrogen (0.008 kg/m^3) means that, compared to natural gas, hydrogen travels at a higher velocity in the NG pipelines [1]. The density of natural gas and hydrogen of 74.62 kg/m3 and 0.008 kg/m3 respectively are at 100 Bar and 303 K [1].This higher velocity of hydrogen in comparison to NG does not cause any safety concerns unless it reaches the erosional limit above which its contact with the pipeline internal walls increases the pipe's vulnerability to internal erosion and failure [1]. Theoretically, there is no limit for gas velocity in pipelines [1]. Nevertheless, a maximum of 20 m/s is recommended to prevent the erosion of pipelines internals [1].

The commonly used equation for the determination of erosional velocity is the API RP 14E [46]

$$V_e = \frac{C}{\sqrt{Pm}} \quad (2)$$

where:

- V_e = fluid erosional velocity, (feet/s)
- C = empirical constant
- ϱ_m = gas/liquid mixture at flowing pressure and temperature, (lbs/ft^3)

For continuous service Values of c = 100 and for intermittent service, c = 125 [46] However, at times, this is considered too conservative and unsuitable because it is designed to be used in the design of new offshore piping systems [40]. Equations 3 is used for determining the gas pipelines erosional velocity limit [1].

$$V_e = \mathrm{N}\,\frac{C}{\sqrt{P}} \quad (3)$$

- V_e = erosional velocity (m/s)
- N = constant (1.22) to convert equation 2 to metric unit from field unit
- C = the empirical constant (varies from 100 to 250)
- ϱ = gas density (kg/m^3)

Khan, Young and Layzell (2021) also gave equation 4 to calculate the erosional velocity.

$$V_{\max} = 100\sqrt{\frac{0.05131\, Z\, R\, T}{G\, P}} \quad (4)$$

- V_{max} is erosional velocity in m/s.
- P is gas pressure in kPa.
- T is gas temperature in K.
- Z is compressibility factor at pipeline conditions and is dimensionless.
- R is ideal gas constant in (8.314 kPa.m3/kg.mol.K).
- G is gas gravity

Theoretically, there is no limit for the gas flow velocity in pipelines, however, a 20m/s threshold is recommended [1] to avoid internal erosion of pipelines that can be intensified by dust which is common in gas pipelines [1]. For H2 to replace NG in the existing NG pipeline infrastructure, a transport velocity limit of 20m/s should therefore be considered.

5.1.7. Pressure Drop

Pressure drop is one of the most important parameters that should be considered when designing a pipeline infrastructure [17]. A major cause of the pressure drop in pipelines is the frictional losses exerted by the fluid in transport on the walls of the pipes [17].

Gas travels through pipelines when there is difference in pressure (DP). The difference in pressure is the change in the total pressure between two points in a pipeline system [21]. The flow of NG must be adequate to meet the energy demand, and this flow is dictated by the pressure drop in the pipeline [21].

The frictional pressure drop is related to the Darcy's frictional factor of the fluid stream, the Reynolds number and the relative roughness of the pipe as given by Equation 4 [1].

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{\mathcal{E}}{3.7D} + \frac{2.51}{R_e\sqrt{f}}\right) \quad (4)$$

Where:

- f = Darcy's friction factor.
- Re = Reynolds number.
- and ε/D = relative roughness of the pipe.
- f, Re and ε/D are all dimensionless [1].

To deliver the required flowrates, compression stations situated roughly every 100 to 500km along the pipeline are used to boost the pressure lost due to friction [19]. However, the density of hydrogen is much smaller than that of NG, meaning that the pressure drop is less significant for gaseous H2 [21]. If the flowrate of hydrogen is fixed at three times the flowrate of NG to deliver the equivalent energy output, the resulting pressure drop is expected to be equal for both the NG and hydrogen [21]. The implication of hydrogen gas having the same pressure drop as natural gas is that a fixed flowrate of hydrogen gas can be transported over longer distances without the requirement for additional gas compression [44].

5.2. Evaluating the Feasibility of Repurposing of the Existing NG Pipelines for H2 Transport

Based on the impacts of technical measures reviewed in section 4, Table 4 has been developed to summarise the findings about H2 transport against NG transport, thus enabling the evaluation of the feasibility of repurposing of the existing natural gas pipelines for H2 transport.

Table 4. Evaluating the Feasibility of Repurposing the Existing NG Pipelines for H_2 Transport.

	NG Transport in Pipelines	**H2 Transport in Repurposed Pipelines**	**Implication of H2 on the existing NG Pipeline**	**Possible Mitigations**
Gas Composition	The main component of the NG transported through the NG pipelines is methane (CH_4)	If NG pipelines are repurposed to transport pure H_2 gas, 100% H_2 becomes the major component flowing through the existing NG pipeline	Metal pipelines can be compromised and degraded on prolonged exposure to H2 gas at high concentrations and pressure	Proactive monitoring and rigorous assessment of the pipelines welds and joints will help identify any possibility of embrittlement and pipeline degradation
Operating Pressure	The NG pipeline infrastructure can be operated up to	The maximum operating pressure of a pipeline transporting H_2	Pressure increase will impact embrittlement which can compromise	H2 transport should typically be operated between 30 and 100Bar at < 50°C

	138Bar at operating temperatures between 6.7°C to 60°C.	gas is 100 Bar at about 20°C	operational safety.	utilising pipelines of low strength material grades (<API X46) and high strength material (X52).
Operating Temperature	Due to JT effect, when the pressure of NG is reduced, temperature drops by 0.5°C for every 1Bar reduction. JT effect in NG can plug transmission materials and cause safety issues.	In H_2 pipelines, when pressure is reduced, H2 temperature increases by 0.035°C for every 1Bar reduction, thus no JT issues.	For H_2 transport, JT effect does not negatively impact the existing NG pipelines.	
Volumetric Energy Density	NG volumetric energy density (35.8MJ/Sm^3) is three times the volumetric energy density of H_2 (10.8 MJ/Sm^3)	H2 less volumetric energy density (10.8MJ/Sm^3) is expected to make its flowrate in the NG pipeline much greater.	Erosional velocity can be exceeded, with consequences of pipeline erosion and leakage.	Maintain the H_2 transport velocity below the erosional velocity.
Operating Density	NG density is much greater than the H_2 gas density	H_2 is the lightest molecule with a very small density, 0.08375kg/m^3	H_2 low density means that it travels faster compared to NG in gas pipelines with potential safety concern if the higher velocity reaches erosional limit.	Maintain the H_2 transport velocity below the erosional velocity.

From table 4, it can be seen that the main component of the NG transported through the NG pipelines for industrial and commercial applications is methane; therefore, if the NG pipeline is to be repurposed for the transportation of pure hydrogen gas, the hydrogen composition will be a determining factor on the degree of embrittlement [17] where Metal pipelines can be compromised and degraded on prolonged exposure to hydrogen existing at high concentrations and pressures [1]. Rigorous assessment of the pipelines, welds and joints will give an indication of the likelihood of future H_2 embrittlement and pipeline degradation [21].

It can also be seen that the transmission of natural gas in the pipeline infrastructure can be operated at up to 138 Bar at operating temperatures between -6.7°C to 60°C, whereas the maximum operating pressure of the pipeline if transporting H2 is 100Bar at about 20°C [18], any increase in the pressure increases embrittlement [1,13,17,45]. Because of the embrittlement concerns H2 transport is typically operated between 30Bar and 60Bar utilising low strength steel (API 5L A, B, X42, & X46) and X52 material grade pipelines [16,18,19,37].

Regarding the JT Effect, when the pressure of NG is reduced, temperature drops by 0.5°C for every 1Bar reduction [9,21] and this may impact the pipeline materials. J-T effect in NG transmission can plug transmission materials and cause safety issues. However, in H2 transmission, there is no safety concerns with J-T effect [9,17,21] because when the pressure is reduced, H_2 temperature increases by 0.035°C for every 1 Bar reduction [9,21].

Volumetric energy density wise, NG is thrice (35.8MJ/Sm3) that of Hydrogen (10.8MJ/Sm3) [19] and this low Hydrogen volumetric energy density presents transportation challenge [19]. For H2 to transport the same amount of energy as NG in the pipeline at the same pressure and temperature conditions, its flowrate velocity is expected to be much greater [19]. This high flowrate can present safety issues as the erosional velocity can be exceeded, with a consequence of pipeline leakage [19]. Therefore, for H2 to replace NG in the existing NG pipeline infrastructure, its transport velocity should be maintained below the erosional velocity, above which its contact with the pipeline internal walls increases the pipe's vulnerability to internal erosion and failure [1]. Theoretically, there is no limit for gas flow velocity in pipelines, however, a 20m/s threshold is suggested to avoid internal erosion of pipelines that can be intensified by dust which is common in gas pipelines [1].

6. Reflective Analysis on the Repurposing Existing NG Pipelines for H2 Transport

Based on last section evaluation, this paper demonstrates the possibility of repurposing the existing NG pipelines infrastructure for hydrogen transport. Using technical parameters such as the operating pressure, temperature, pressure drop, volumetric energy density and density as criteria, the possibility of repurposing the existing NG pipelines infrastructure for hydrogen transport was conducted.

The operating pressure and temperature conditions for the transportation of gaseous H2 is well within the range which the NG pipelines are typically operated. Typically, the existing NG pipeline is operated between 10Bar and 138Bar and at temperatures between -6.7°C and 60°C when transporting NG, therefore, it can be operated between 30Bar and 100Bar and at less than 50°C to safely transport gaseous hydrogen.

To contain the threat of pipeline embrittlement when transporting H2, materials grades X52 and below are more ideal to use. High-strength steels which offer a substantial cost benefit of 10 to 40% [38] are known to be more prone to H_2 embrittlement [19]. Nonetheless, with major modifications, higher strength steel grades can be utilised to transport pure H_2. Degradation Inhibitors such as oxygen (O_2), sulphur (IV) oxide (SO_2), & carbon monoxide (CO) and Pipe in-Pipe technology can be used to modify the existing NG pipelines constructed from higher strength steels [39]. Degradation inhibitors can be injected into the existing pipeline to inhibit the process of H_2 embrittlement. Utilising Pipe in-Pipe technique an inner pipeline material that is not prone to embrittlement can be inserted in the existing pipeline to screen the pipeline from hydrogen gas [39]. Other pipeline materials that can be used to transport hydrogen is Polyethylene (PE) because, based on the undertaken reviews, there is no evidence that Polyethylene (PE) materials are susceptible to embrittlement. However, Polyethylene (PE) materials are typically rated for 17.5 Bar and should not be used to transport gaseous hydrogen at elevated pressures.

Pressure drop (DP) should not pose any serious issue for the transport of gaseous H_2 in the existing NG pipelines due to the very low density of H_2 compared to NG. If the flowrate of hydrogen is fixed at three times the flowrate of NG to deliver the same energy, the pressure drop for H2 gas and NG is expected to be equal [21] and hydrogen gas can be transported over longer distances than expected without the requirement for additional gas compression [44].

While the J-T effect in natural gas transport can plug the pipeline materials and cause safety issues, H2 transport does not impact the existing NG infrastructure negatively.

The low volumetric energy density of Hydrogen presents a transportation challenge because the flow rate of H_2 must be increased to transport the same amount of energy. Increasing the flowrate can cause flow velocity to increase. Therefore, for H2 to be transported in a repurposed NG pipeline, the flow velocity must be monitored and kept below the erosional velocity to prevent the pipeline internals from eroding.

In conclusion, based on the above assessment criteria, it may be possible to repurpose the existing NG pipelines infrastructure for hydrogen transport.

7. Conclusions

Based on the undertaken review of the different options for H2 transport and based on the assessment of the feasibility of repurposing the existing NG pipelines for H2 transport using technical criteria, several outcomes that offer encouragement for the repurposing of the existing natural gas pipeline infrastructure emerged.

A major outcome is the obvious advantage of the transport of H2 as gas in pipelines, particularly, for short to medium distances. This option is characterized by the continuous delivery of non-toxic H_2 gas which is highly dense in energy. The high energy density and the continuous supply characteristic of this option make the most viable choice. However, for Hydrogen to replace natural gas in the existing NG infrastructure, the flowrate of hydrogen gas is expected to be fixed. Hydrogen gas must flow at three times the flowrate of natural gas to deliver the same energy. Fortuitously, the very low density of H_2 compared to NG means that pressure drop (DP) should not pose any serious issue for the transport of gaseous H2 transport using the existing NG pipelines. Subsequently, this fixed flowrate is expected to allow hydrogen gas to be transported over longer distances without the requirement for additional gas compression.

Maintaining the transport velocity of the hydrogen gas below the erosional velocity is essential to safeguarding the operating and safety integrity of the existing natural gas pipelines. The H2 transport velocity in the repurposed NG pipeline must be kept below the erosional velocity which has been recommended to be below 20 m/s. Keeping the transport velocity below 20 m/s is critical in preventing the erosion of pipelines internals.

Furthermore, unlike natural gas, the J-T Effect does not create operational safety issues if H_2 is transported in repurposed NG pipelines. This attribute of hydrogen gas generates opportunities for safe transportation of hydrogen gas, an encouraging development for the repurposing of natural gas pipelines for hydrogen gas transportation.

From pipeline materials perspective, it is possible to repurpose the existing natural gas pipeline for hydrogen gas transportation. The maximum operating pressure of a pipeline transporting H_2 is 100 Bar at about 20°C. As pressure increases the impact of embrittlement, materials grades X52 and below are more ideal to use to transport H_2 in NG pipelines at reduced pressures of 30 Bar to 60 Bar to contain the threat of H_2 embrittlement. Low strength steel of material grades API 5L A, B, X42, & X46 and X52 are considered not susceptible to hydrogen embrittlement at normal operating conditions. Therefore, with no modification, it's possible to reuse the existing NG pipeline that are constructed from low strength steel below X46 and X52 to transport pure hydrogen gas.

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With major modifications, higher strength material grades (X56, X60, X65, X70, & X80) pipelines can be repurposed to transport pure H2. Degradation inhibitors (O2, SO2, & CO) and pipe-in-pipe technique can be applied to modify the existing NG pipelines constructed from higher strength steels. Injecting the degradation inhibition gases into the steel material pipeline can prevent gaseous hydrogen from being absorbed into the pipeline material [39]. In the pipe-in-pipe (PIP) technique, an internal pipe is installed into the existing steel pipeline to provide a barrier between the steel pipeline and hydrogen gas. This internal pipe is constructed from a material that can withstand the challenges that the hydrogen gas poses. Polyethylene are the most utilised inner pipes in oil and gas facilities [39].

Table 5 summarises the pipeline material grades that can be used for H2 transport at equivalent operating pressure.

Table 5. Material Grades for H2 Transport.

Material Grade	Hydrogen Concentration	Operating Pressure
Low strength steel (API 5L A, B, API 5L X42 & X46)	100%	30 to 100 Bar
High strength steel (API 5L X52)	100%	30 to 100 Bar
Polyethylene (PE)	100%	< 17.5 Bar
High strength steel (API 5L X56, X60, X65, X70, X80)	100%	< 100 Bar (With major modifications)

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Abbreviations

H_2 Hydrogen
NG Natural Gas
LH_2 Liquified Hydrogen
BP Boiling Point
BOG Boil Off Gas
Mw Molecular Weight
LOHC Liquid Organic Hydrogen Carrier
MCH Methylcyclohexane
NH_3 Ammonia
CH3OH Methanol
CO2 Carbon Dioxide
CO Carbon Monoxide

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Km Kilometre
DP Pressure Drop
J/Scm Joules per Standard cubic metre
Btu/Scf British thermal unit per Standard cubic metre
CH4 Methane
JT Joule Thomson
PE Polyethylene
ASME American Society of Mechanical Engineers
O2 Oxygen
SO2 Sulphur (IV) Oxide
°C Degree Celsius
PIP Pipe-in-Pipe
MOP Maximum Operating Pressure
GHG Green House Gas
K Kelvin

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