Appendix I

Literature Review

(Internal R&D)

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Introduction

Access to affordable and abundant energy can drive economic development and enable a higher quality of life. Modernization of society requires energy. Figure 1-1 depicts projections for future global primary energy demands until 2040 by the Energy Transition Commission (IEA, 2018). Energy consumption per capita has increased 62% globally since 1965, whereas, for North America, the increase is 19% (Hannah Ritchie, 2020). Figure 1-2 shows per-capita energy consumption for different regions of the world. The International Energy Agency (IEA) forecasts demand will increase to 16.2 gigatonnes of oil equivalent (Gtoe) by 2030 (IEA, 2018). Though traditional fossil energy sources (coal, gas, oil, etc.) currently play substantial roles in the global energy sector, environmental issues such as air pollution, global warming and climate change have gained significant attention. The combustion of fossil fuel, the emissions of carbon dioxide (CO_2), and other greenhouse gases (GHG) are identified as the primary reasons for these issues (Guoping Hu, 2020). A study by Chu, Cui, and Liu exhibits that the GHG level in the atmosphere is more than 480 ppm (Chu, 2017) [4], which is approximately 50% higher than the pre-industrial level (Betts, 2021) . As a result, the existing energy sector will be required to achieve significant reductions in carbon emissions to mitigate the effects of climate change. Hydrogen presents a pathway to decarbonize portions of the economy and hard-to-abate sectors. Utilizing existing infrastructure (such as through blending of hydrogen into the existing natural gas network) can allow for more widespread adoption of hydrogen by inducing the requisite demand to underpin future projects.

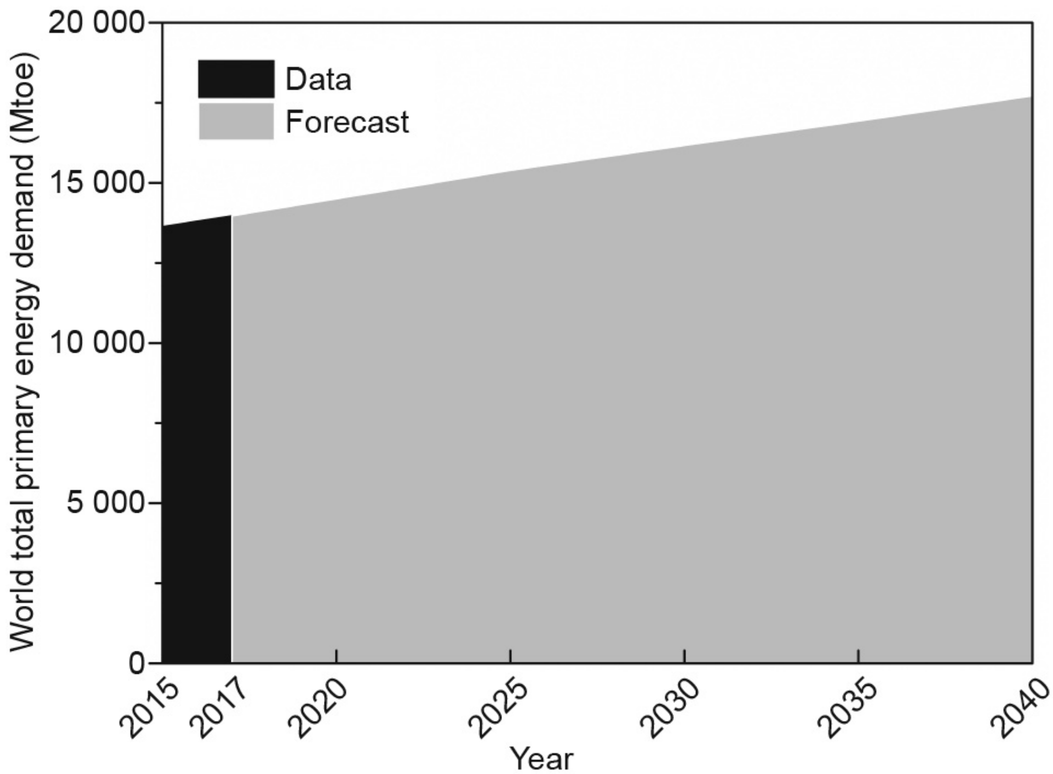
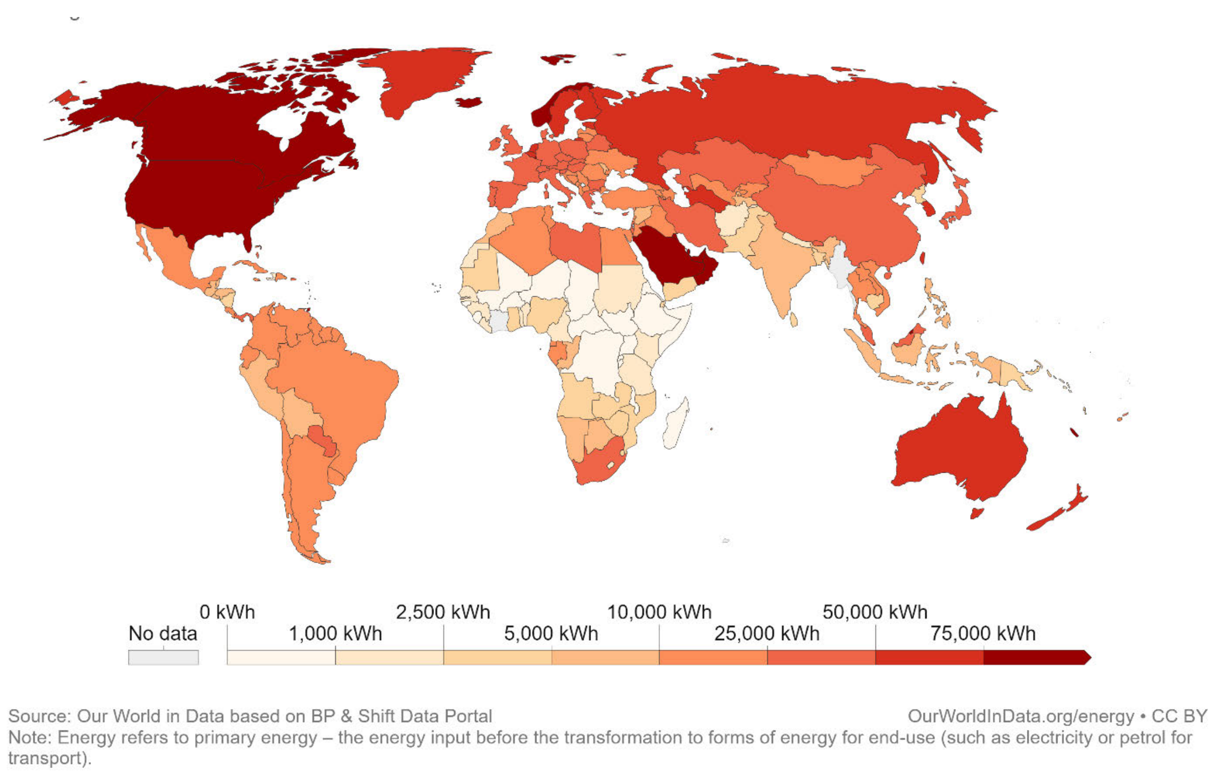


Figure 1-1: Global primary energy demand (new policies scenario) in 2015, 2017, and forecasted until 2040. Mtoe: million tonnes of oil equivalent (IEA, 2018)



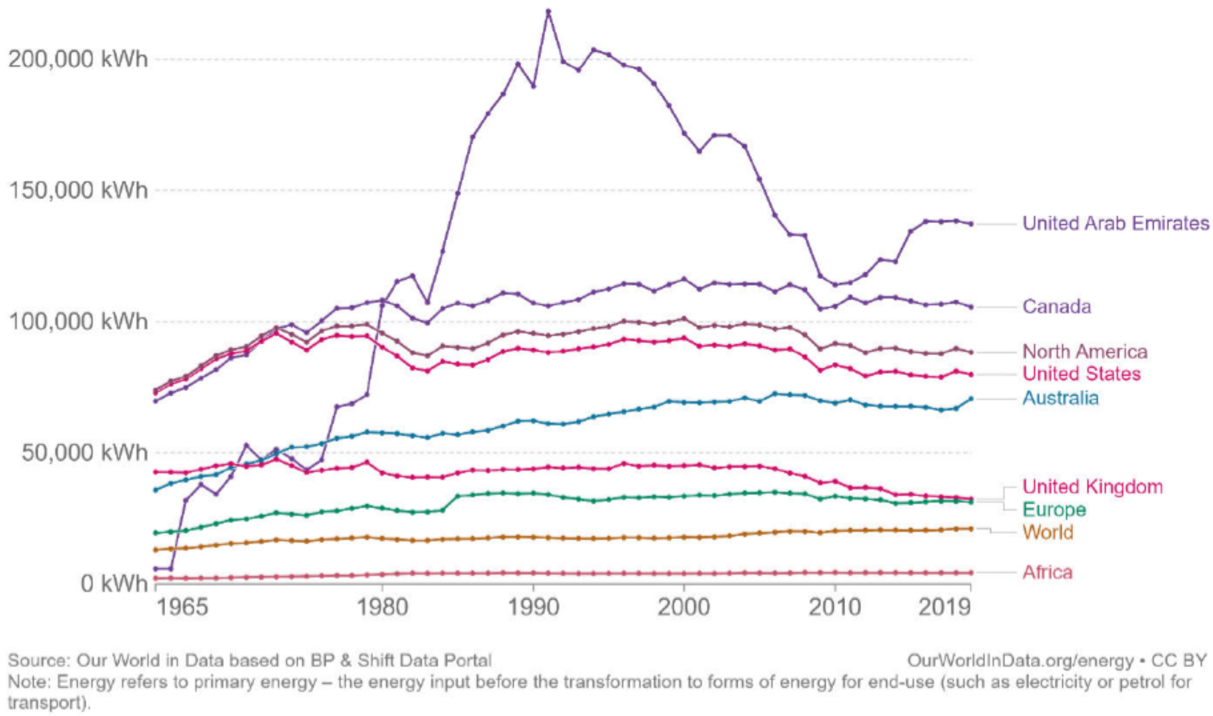


Figure 1-2: Energy use per person - (a) by map, (b) by chart. (Our World in Data) **(Hannah Ritchie, 2020)**

Renewable energy is a popular solution to battle against climate change. Renewable energy sources include solar, wind, tidal, biomass, etc. Even though these sources produce net-zero carbon emissions, the primary concerns are their effectiveness as a continuous energy source and whether they can be transported and stored. The use of renewable energy also requires new carbon-free energy carriers such as batteries, compressed air, hydrogen, etc. (Abdel-Nasser Cherigui, 2009) (Willian Cézar Nadaleti, 2020). Hydrogen is a promising carrier due to its relatively high energy density, low energy loss, and application as a clean versatile energy form (M. Schmidt, 2019) [redacted]

Hydrogen is considered a viable alternative to natural gas in the long-term; however, a challenge is the long-distance transportation from the production site to end users. The most economic long-term solution is pipeline transportation. Construction of new pipelines and repurposing of existing hydrogen-compatible infrastructure (including station facilities and end-user appliances) are proposed to minimize the need for significant time and capital investments. As a result, hydrogen blending with natural gas is proposed as a short to medium-term 'bridge fuel' and transitional solution to leverage existing natural gas transportation assets and provide a pathway towards zero-emission fuels (Joan Ogden, 2018).

The hydrogen blending concept is being investigated by many major energy companies. The 2015 Paris Agreement, a legally binding international treaty on climate change (adopted by 196 parties), aims to limit global warming to around 1.5-2°C compared to the pre-industrial age. The first step is to reduce greenhouse gas (GHG) emissions, adopt low-carbon solutions, and finally move towards zero-carbon clean energy (UNITED NATIONS , 2015). The Government of Canada has declared a climate plan to achieve the Paris Agreement target by lowering GHG emissions by 40-45% by 2030 from the 2005 level, and achieving net-zero emissions by 2050, as confirmed through the Canadian Net-Zero Emissions Accountability Act (which became law on June 19, 2021) (Government of Canada, 2022). The Ontario Ministry of the Environment, Conservation and Parks also declared their Made-in-Ontario environmental plan aligned with Canada's 2030 target (Government of Ontario, 2020). Their plan commits to reducing GHG emissions by 30% by 2030. Major energy companies are working to develop the hydrogen energy sector as one of the means of achieving carbon reductions. [redacted]

Countries around the globe are working on developing hydrogen strategies and roadmaps to develop a stable hydrogen economy. As of 2020, eighteen countries have developed national hydrogen strategies (figure 1-3). Collectively, these 18 countries account for more than 70% of global GDP (NRCAN, 2020). In Canada, each region uses different input sources for power generation based on available feedstocks; hence, the low-carbon energy transition roadmap varies based on currently available energy sources. For example, in Saskatchewan, the current primary power generation source is coal; however, Saskatchewan is aiming to shut down coal-based power plants by 2030 and move towards nuclear power plants to reduce carbon emissions. Figure 1-4 shows the potential provincial energy transition roadmaps for different regions of Canada.

In any scenario, all levels of government (federal, provincial and local) and industries need to work in harmony to develop the most economical and efficient pathways. A balanced, collaborative approach will lead Canada towards a zero-emission energy sector.

Figure 1-3: Global Hydrogen activity (NRCAN, 2020)

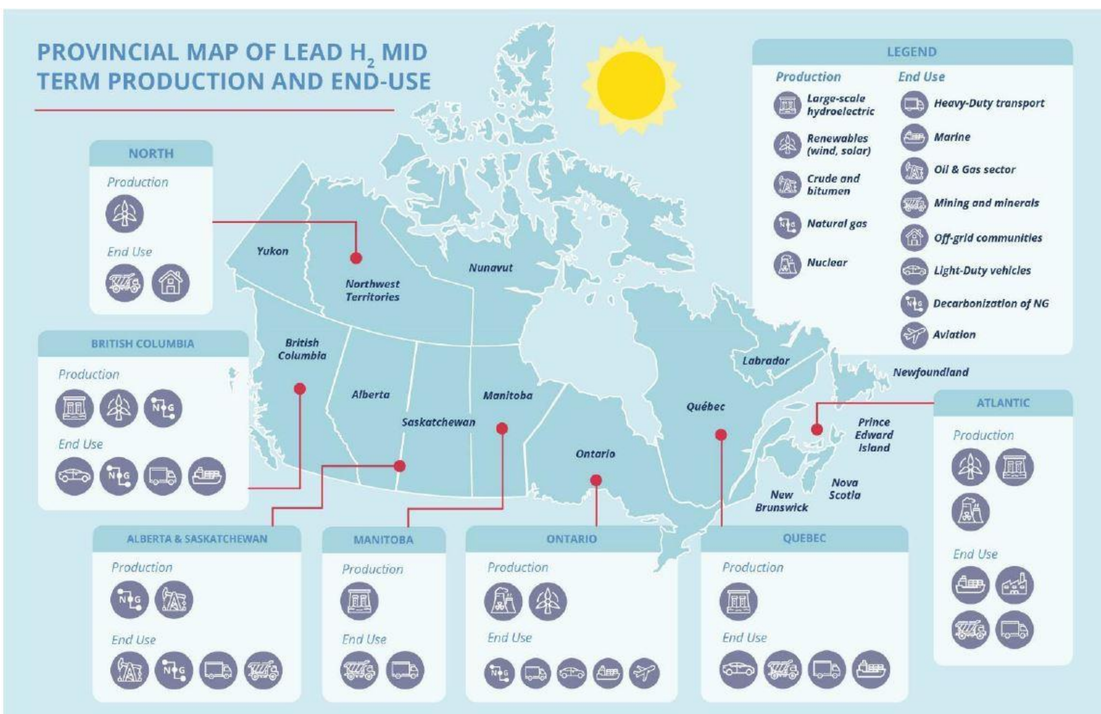


Figure 1-4: Provincial roadmaps towards low-carbon energy (NRCAN, 2020)

Hydrogen and natural gas blending technology are still at the early stages of development. Hydrogen compatibility of existing pipeline, station and end-user assets is not well defined. The addition of small concentrations of hydrogen may demand major modification to structural and equipment materials, design, and maintenance of the system (Ez-Zaki, 2020), (Thanh Tuan Nguyen N. T., 2020); hence, a case-by-case engineering assessment is necessary to introduce hydrogen-blended natural gas to any network. Research studies are being carried out around the world for a better understanding of the requirements for operating a safe, affordable and reliable hydrogen-natural gas blended grid.

This literature review was conducted to summarize the latest state of research and development on blended hydrogen-natural gas based on publicly available data and aims to:

- Identify technical knowledge gaps and opportunities
- Examine primary failure mechanisms for hydrogen in metallic and non-metallic piping
- Review basic fluid characteristics of blended hydrogen-natural gas mixtures
- Present regulatory, financial, economic and technological challenges and opportunities
- Summarize the theoretical hydrogen blending capability of existing natural gas assets
- Discuss known blended hydrogen-natural gas projects around the world

Knowledge Gaps & Opportunities

Existing gas distribution assets were designed and manufactured for natural gas transportation, and their hydrogen compatibility is not well established. Hence, incorporating hydrogen-blended natural gas may entail challenges, such as material sensitivities, asset lifetime evaluation, economic concerns, regulatory modifications, etc.. Areas of the gas distribution system affected by hydrogen injection are discussed below.

2.1 Asset Capability

It is established that hydrogen can potentially modify the material's properties. In the gas distribution system, the primary transportation media are steel and polyethylene (PE) pipes. If blended gas (hydrogen + NG) is introduced to the existing network, hydrogen can permeate through steel, make the material brittle, and cause an effect known as hydrogen embrittlement (see Section 3). In addition, hydrogen may alter the pipeline steel's properties, specifically the microstructure, mechanical properties, fracture, and fatigue properties. On the other hand, in PE pipe transportation, the gas leakage rate is higher due to lower molecular weight and higher diffusivity of hydrogen. Other asset materials also pose either leakage risk or vulnerability to material degradation when exposed to hydrogen. The effect of hydrogen on the properties of the material are as follows:

2.1.1 Effect of Hydrogen on Material Properties

Due to its very small size, hydrogen can enter and escape through the material body (permeation and diffusion) and change its properties. The significant factors responsible for this are (a) permeability, (b) diffusivity, and (c) solubility. Permeability is the rate at which gas enters (permeates) through a metallic or polymeric body. The hydrogen permeation coefficient is the measure of the ability of hydrogen to permeate through a specific membrane (Asuka Suzuki, 2020). The higher the permeation coefficient number, the greater the chance that hydrogen will permeate through the body and modify the mechanical and metallurgical properties of the material. Diffusion can be defined as the transportation of the hydrogen atom through the metal lattice. For metal, the hydrogen atom permeates through the metal body and is then randomly distributed among the metal atoms (Fallahmohammadi, 2011). The diffusible hydrogen can be trapped in structural defects or form hydride phases.

The total amount of hydrogen inside the material (trapped and normal site) can be referred to as hydrogen solubility (Y. Matsumoto, 2014). When exposed to the metal surface, hydrogen dissociates into atoms, enters the metal surface, is transported through the metal body, and is trapped in the lattice or forms hydrides. The partial pressure of the trapped hydrogen makes the material brittle, modifies material properties, and could potentially cause failure. The entire phenomena can be described collectively by permeation, diffusion, and solubility of hydrogen (San Marchi, 2012). However, it is important to note that, operating temperature and pressure have a significant impact on hydrogen degradation and potential for leakage.

Numerous research works have been carried out to evaluate the effect of hydrogen on the mechanical properties of structural and alloy steels (San Marchi, 2012), (Thanh Tuan Nguyen J. P., 2020), (Thanh Tuan Nguyen J. S., 2021), (Michler T, 2021), (Piche, 2020), (Bo Meng, 2017), (I.M. Dmytrakh, 2015), (Brian Somerday, 2008), (Hanneken, 1999). Though there are a few contradictory reports (V.G. Gavriljuk, 2003), (W. Godoi, 2003), the general effect of hydrogen on materials is well established.

2.1.2 Tensile Properties

Hydrogen is not expected to exhibit any significant effect on the yield strength (YS) and the ultimate tensile strength (UTS) of a material based on recent studies (San Marchi, 2012), (Thanh Tuan Nguyen J. P., 2020), (Thanh Tuan Nguyen J. S., 2021), (Michler T, 2021), (Piche, 2020), (Bo Meng, 2017), (I.M. Dmytrakh, 2015), (Brian Somerday, 2008), (Hanneken, 1999). However, ductility, fracture toughness, and reduction of area at the fractured zone may be affected because of hydrogen exposure (Thanh Tuan Nguyen N. T., 2020).Figure 2-1 shows the comparison of test results from Sandia National Laboratory for an air/inert environment and hydrogen (San Marchi, 2012).

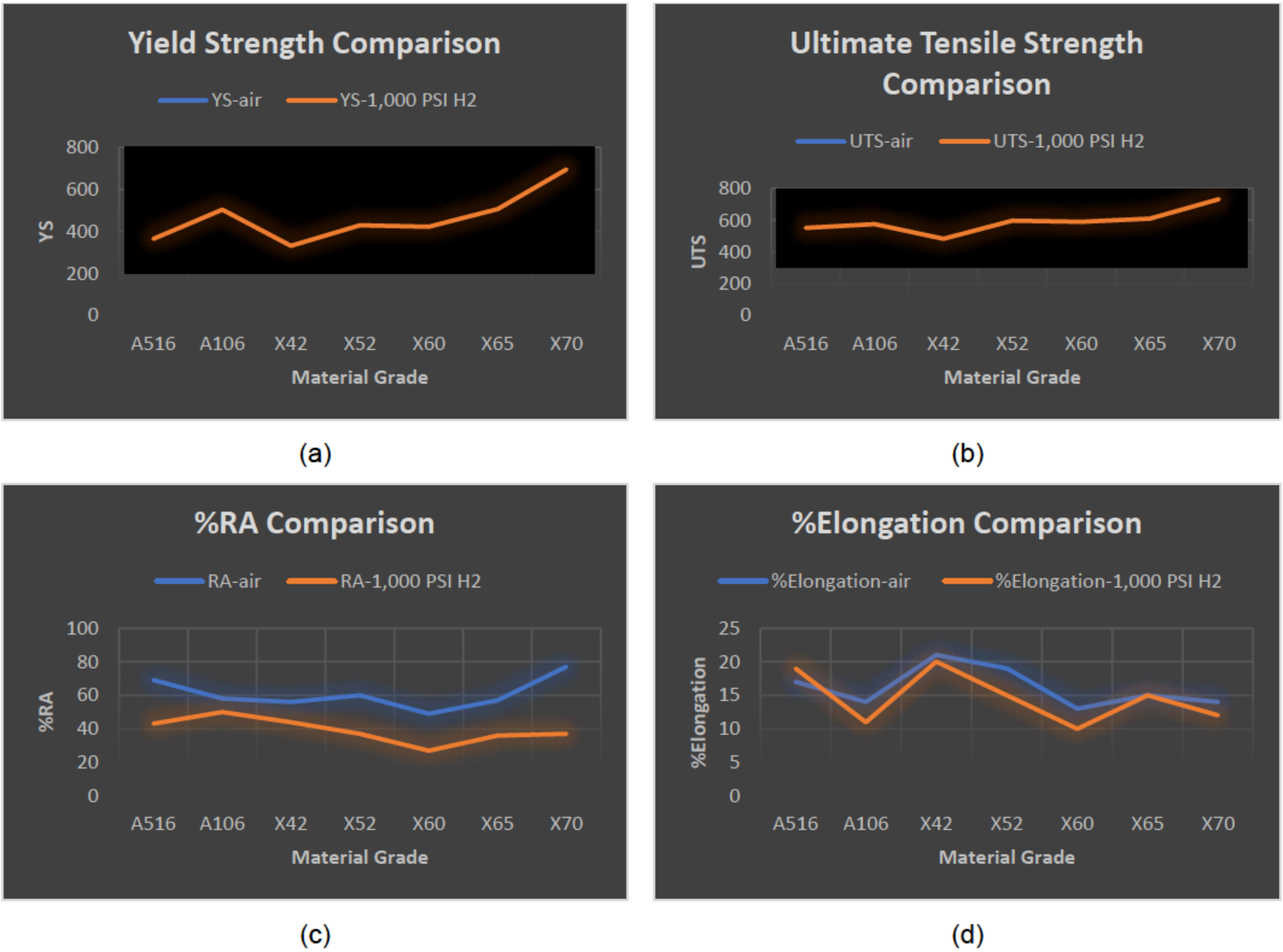


Figure 2-1 No significant changes in YS and UTS properties were observed in hydrogen, while %RA and %elongation were reduced

The findings are slightly different for stainless steel. Figure 2-2 shows the tensile properties of stainless steel in air and hydrogen. As seen for carbon and HSLA steel, no significant alteration is observed for YS and UTS; however, the ductility of the stainless-steel shows diverse behaviour for different grades. Martensitic and ferritic stainless steel exhibits reduced %RA and %elongation due to hydrogen, whereas austenitic stainless steel shows no significant change. This can be explained by the crystallographic structure of austenitic stainless steel which inhibits hydrogen from making the material brittle.

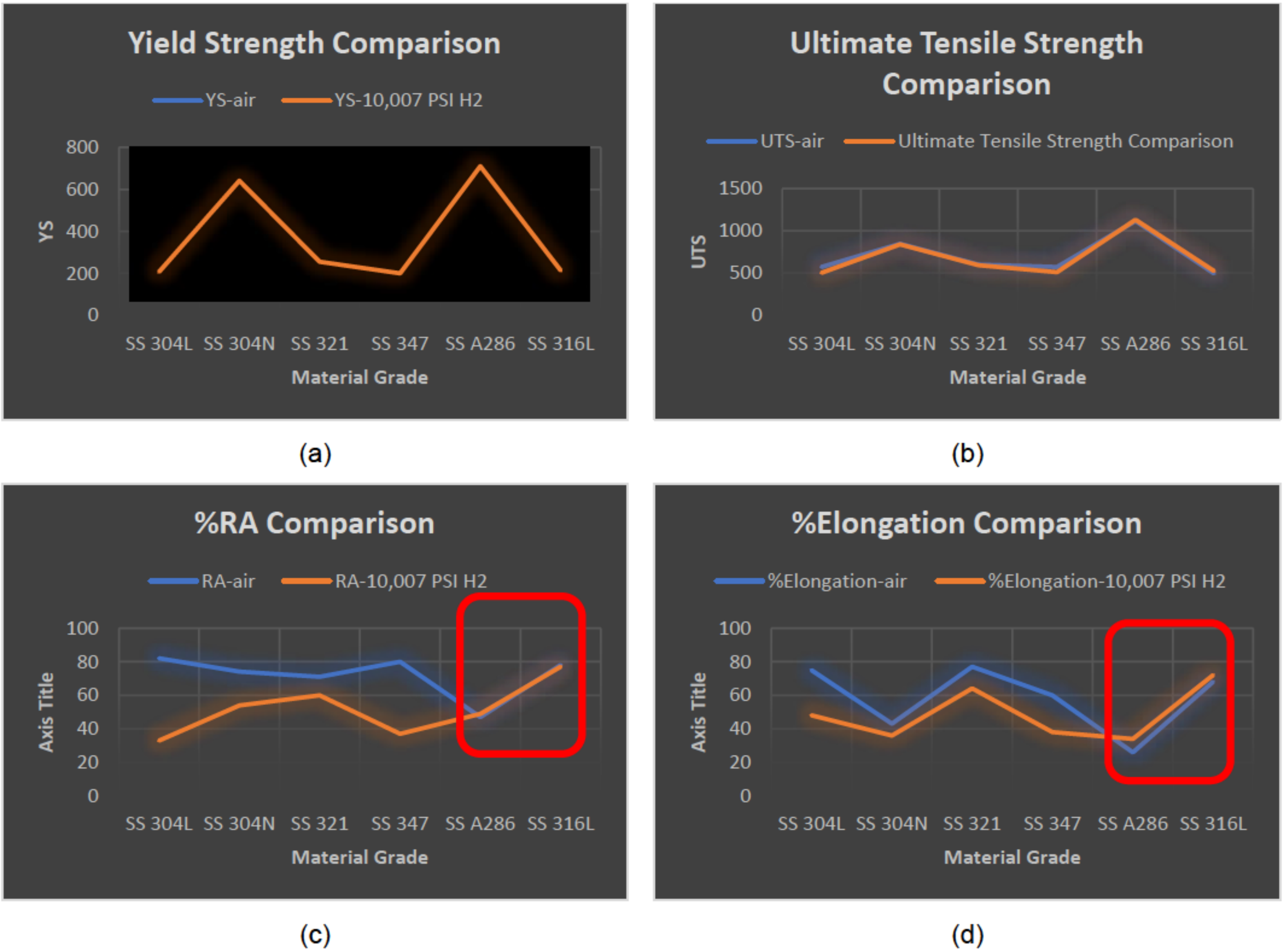


Figure 2-2 Tensile properties comparison of stainless-steel material under air and hydrogen environment. (a) yield strength, (b) tensile strength, (c) %reduction of area at fracture, and (d) %elongation (all data collected from the report published by Sandia National Laboratory

Other studies have reported a similar trend. Nguyen et al. performed tensile tests on hydrogen-exposed API X70 line pipe steel. The results showed no significant changes in UTS but reduced %RA and fracture elongation (Thanh Tuan Nguyen N. T., 2020). Table 2-1 summarizes their findings. Meng et al. reported no substantial changes in tensile properties and reduced %RA and %elongation with increasing hydrogen. Figure 2-3 shows the summary results published by the authors (Bo Meng, 2017).

Table 2-1 Summarized test conditions and results of the smooth tensile specimens.

Test condition	Number of tests	UTS (MPa)	%RA	%EL (fracture)
atm, RT	6	632 ±2	82 ± 0.70	23.3 ± 1.53
1% mixture gH2, 10 MPa	6	624 ± 3	81.7 ± 2.1	22.4 ± 0.81
1% mixture gH2, 10 MPa, 720-h exposure	6	620 ± 3	81.3 ± 1.8	22.7 ± 0.50
100% He, 10 MPa	2	628 ±3	82 ± 0.65	21.15 ± 0.25
100% H2, 10 MPa	2	628 ± 1	40.2 ± 5.1	15.52 ± 1.42

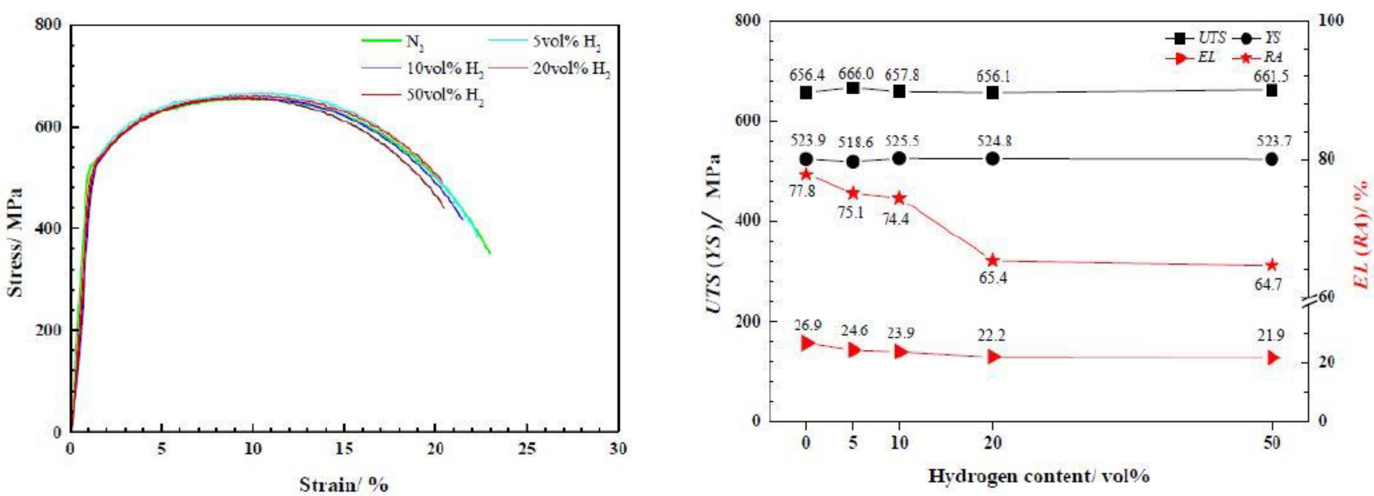


Figure 2-3 Influence of added hydrogen on the tensile properties of smooth-tension specimens (Bo Meng, 2017)**.**

Recent studies exhibit that hydrogen concentration and exposure time do not affect the YS and UTS of welds. A recent work by Austin Piche tested Gr. 290 line pipe steel exposed to 0 vol%, 5 vol%, and 20 vol% hydrogen and tested the sample after two weeks, two months, and six months respectively. Figure 2-4 shows the test result summary of the weld material for different hydrogen conditions. The results suggest that hydrogen concentration and exposure time do not affect the tensile properties of welded material. It is interesting to note that this study reported relatively consistent %RA and %elongation results for all hydrogen conditions, which is contradictory to data published by other research (Piche, 2020).

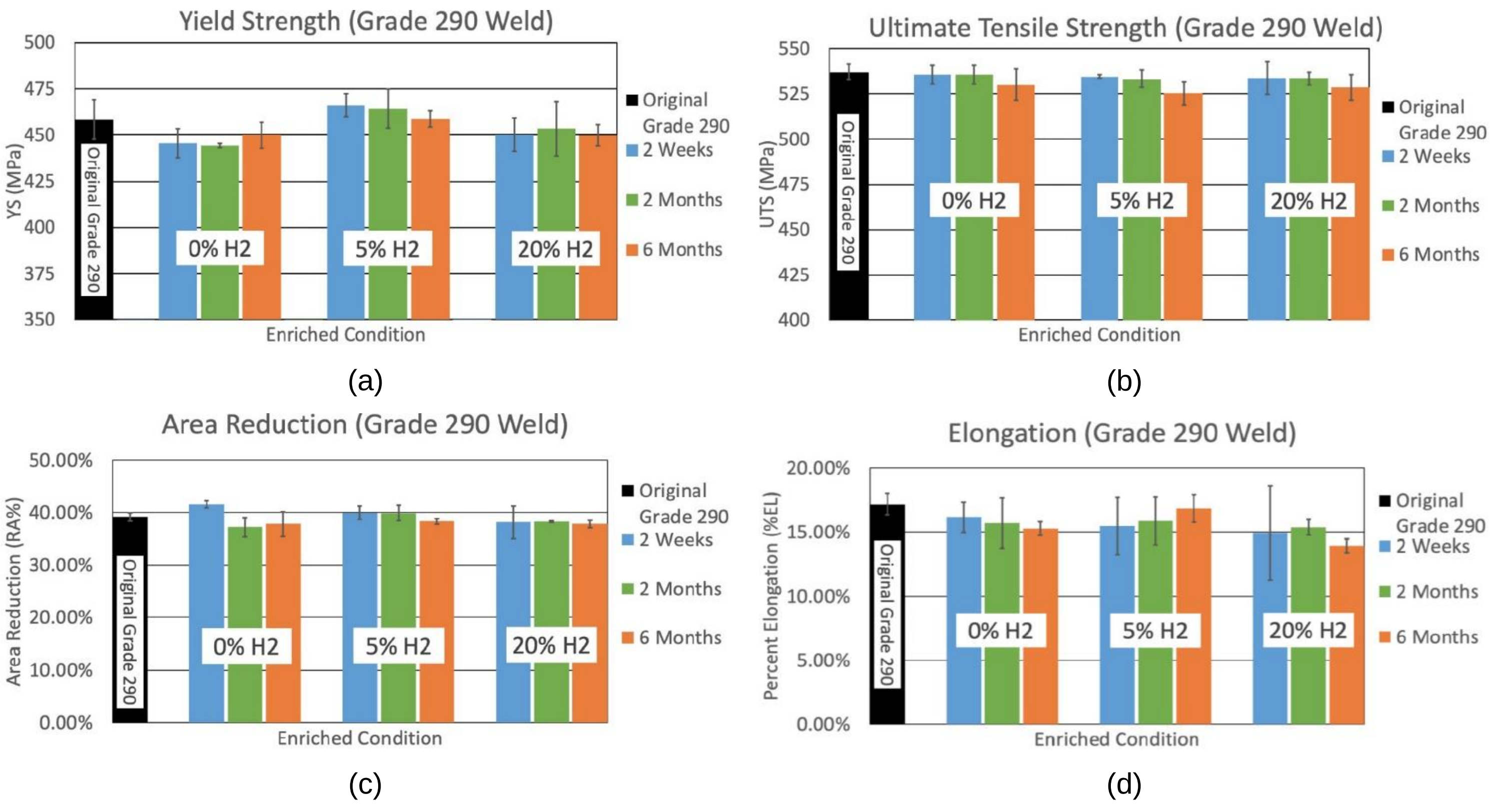


Figure 2-4 Average tensile properties for specimens of Grade 290 welded material for ten blended conditions; (a) YS, (b) UTS, (c) %RA, and (d) %elongation (Piche, 2020).

2.1.3 Fracture Mechanics

The material's ability to resist the propagation of a pre-existing crack can be referred to as fracture toughness. Fracture toughness indicates whether the fracture mode will be ductile or brittle. A material with high fracture toughness is prone to ductile failure and vice versa. The fracture toughness mechanism of steel is complex; however, it depends on pre-existing flaws in the material (cracks, voids, metallurgical inclusions, weld defects, discontinuities, etc.).

Fracture toughness and crack-propagation resistance of steel is reduced in the presence of hydrogen. The concentration of hydrogen at pre-existing cracks is the driving force for crack propagation. In addition, higher temperature and pressure increase the diffusion coefficient of hydrogen in the steel lattice, which reduces fracture toughness (San Marchi, 2012), (Gallon, 2020), and increases stress at the crack tip. Figure 2-5 shows the effects of pressure on fracture toughness of X52 and A516 steel reported by Somerday and Marchi. Their report shows approximately 31-87% fracture toughness reduction for carbon and HSLA steel in gaseous hydrogen (San Marchi, 2012). Other studies reported a ~30-70% reduction in toughness due to the presence of hydrogen (Müller-Syring, 2009), (Barthélémy, 2009).

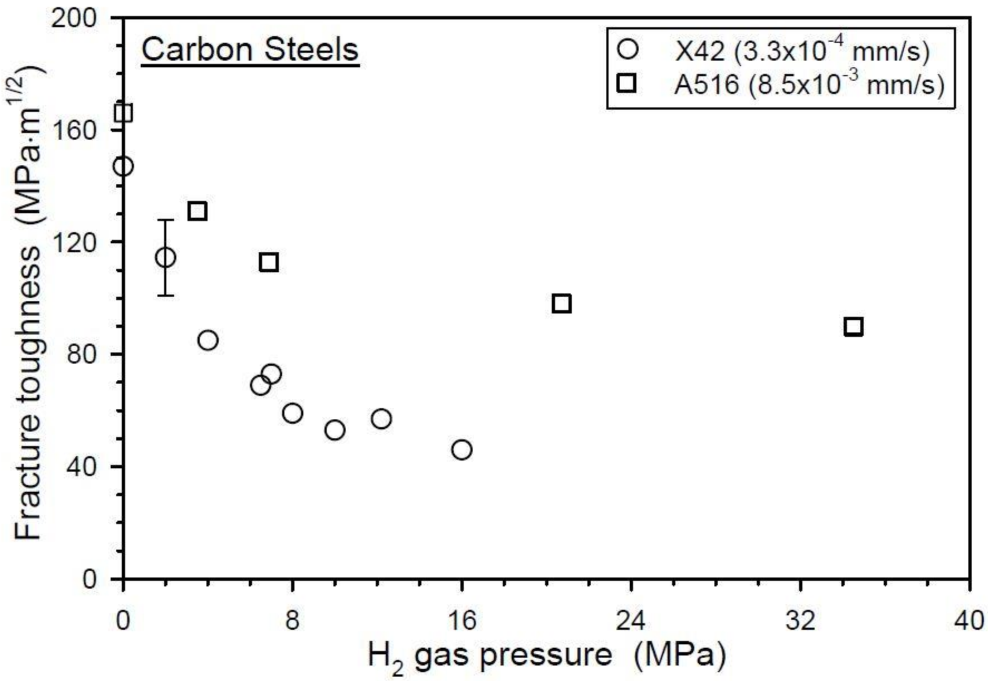


Figure 2-5 Fracture toughness reduction of carbon steel due to increasing pressure (San Marchi, 2012).

It is interesting to note that hydrogen does not show any significant effect on Charpy energy (Li, 2016). As a result, according to a Sandia report, impact toughness property and fracture toughness correlations are not appropriate for understanding of hydrogen-assisted fractures (San Marchi, 2012).

In brief, hydrogen is expected to decrease the fracture toughness of steel; however, the magnitude of this reduction is not clear.

2.1.4 Fatigue Properties

Initiation and propagation of cracks due to cyclic loading is referred to as fatigue. Fatigue failures start from a discontinuity or crack in the material. The first stage of fatigue is crack initiation when the load exceeds the tensile strength of the material. Initially, stresses are concentrated at the tip of the crack. As a result, the crack propagates in stages during the fatigue cycle and eventually ruptures the material.

For a natural gas distribution system, pressure fluctuations in the pipeline during gas transportation are the most probable source of fatigue crack initiation along with external loadings from road crossings for example. Evaluation of fatigue properties of the material is particularly significant given the severity of the failure mode (Bo Meng, 2017), (Mohsen Dadfarnia, 2019). Alvaro et al. reported an approximately 76 times higher crack growth rate for X70 steel for in-situ electrochemical hydrogen charging condition compared to testing in air. This indicates the severity of time-dependent hydrogen-induced degradation. The severity can be explained by the evaluation of the fracture-surface microstructure. Post-mortem of the failed samples showed the presence of brittle quasi-cleavage-type fracture (Antonio Alvaro, 2019). In brief, hydrogen may change the fracture mode from ductile to brittle, and this transition increases the crack growth rate. Nguyen et al. reported similar fracture mode changes for X42 and X70 steel due to the presence of hydrogen (Thanh Tuan Nguyen N. T., 2020), (Thanh Tuan Nguyen J. S., 2021). In their study, they observed two active fracture modes during the small punch test: ductile and quasi-cleavage (brittle). With increasing %H2, they reported fracture mode changes towards more brittle fracture, and the number of crack initiation sites also increased remarkably. Figure 2-6 shows the change of fracture mode and cracks of X42 steel with increasing hydrogen concentrations (Thanh Tuan Nguyen N. T., 2020). It should be noted that this appears to be a time-dependent failure mode. Hence, %brittle fracture will likely increase with exposure time. Austin Piche performed fracture-surface evaluation for different exposure times and found that the percentage of brittle fractures increases with longer exposure time. Figure 2-7 shows the increasing percentage of brittle area of an X42 steel sample for a specific hydrogen concentration and different exposure times; however, the weld zone showed different behaviour with no rising brittle area (Figure 2-8). The internal, induced partial pressure was 60 psig for these experiments (Piche, 2020). An et al. used a different hydrogen partial pressure of approximately 88 psig for their fatigue test on X80 steel, and their study showed a reduced fatigue life cycle with increasing hydrogen partial pressure (Teng An, 2017). Another study by the National Renewable Energy Lab (NREL) stated that accelerated fatigue crack growth is more severe at ambient temperature compared to elevated temperatures. The study also mentions that the presence of hydrogen reduces the cyclic stress intensity factor (ΔK) and fatigue life (M. W. Melaina, 2013).

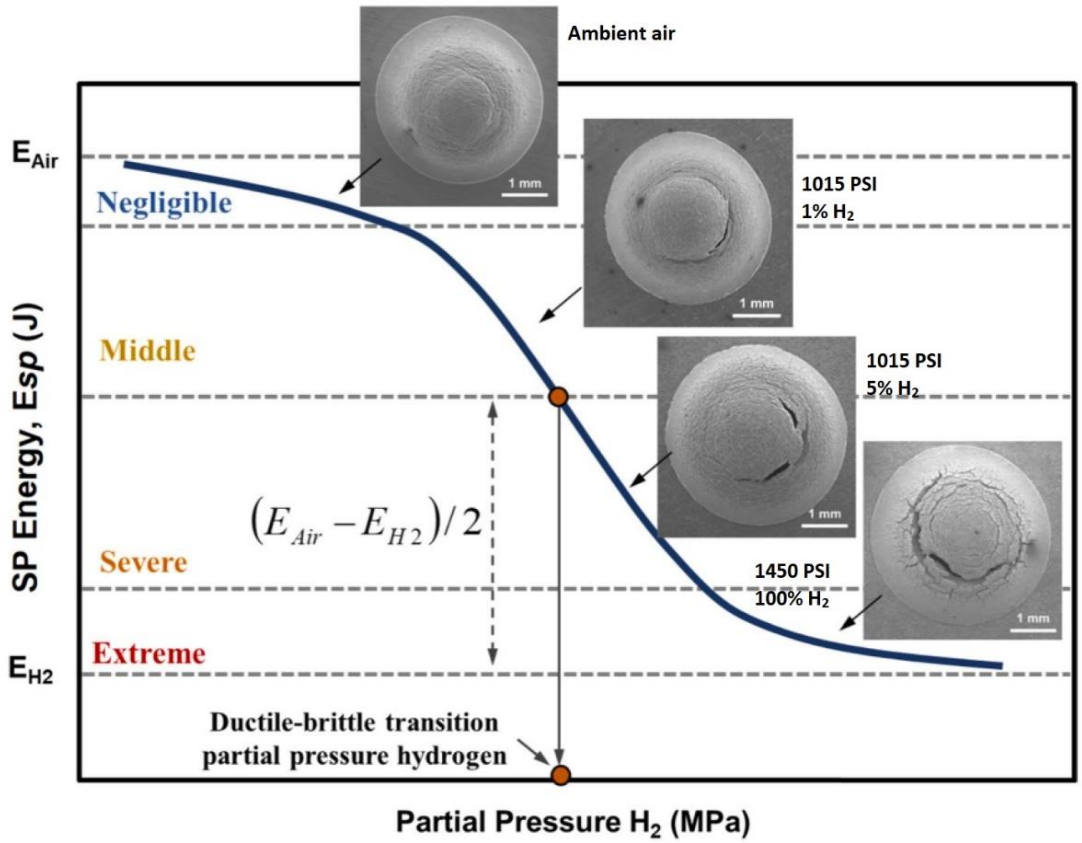


Figure 2-6 Effect of H_2 on the fracture mode of steel (Thanh Tuan Nguyen J. S., 2021)

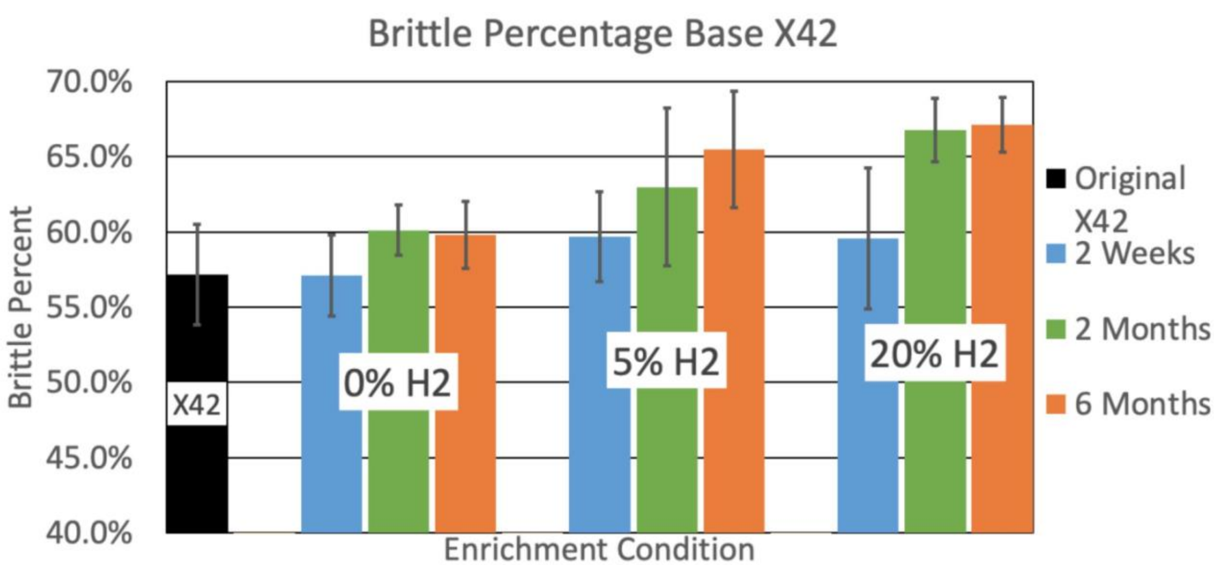


Figure 2-7 Brittle area percentage of X42 pipe sample for different hydrogen-enrichment conditions (Piche, 2020)

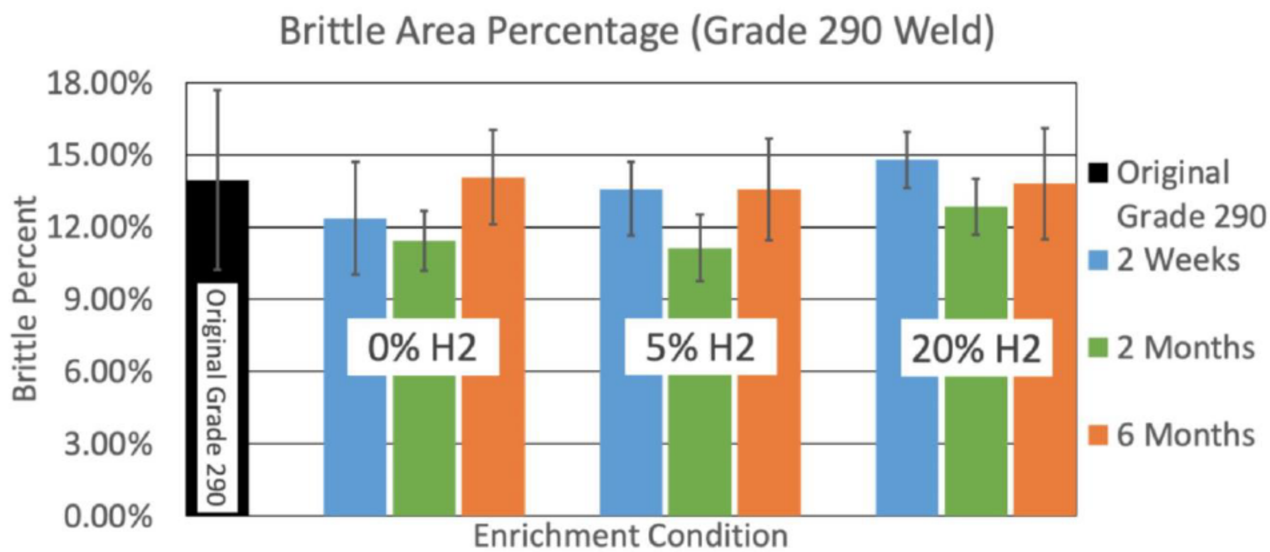


Figure 2-8 %Brittle area of Gr. 290 weld zone for different enrichment conditions (Piche, 2020)

Based on these recent studies, it is apparent that fatigue cracking may be a concern in gas distribution pipelines where pressure fluctuates due to different demands throughout the day. The addition of hydrogen increases the risk of crack growth rate and fatigue failure. The pipeline may have existing discontinuities due to corrosion, sharp defects at the weld, microcracks, voids, inclusions, etc. These existing features may be susceptible to crack initiation and form crack propagation sites. Higher hydrogen concentration and operating pressure increase the risk of fatigue failure (Thanh Tuan Nguyen J. S., 2021), (Thanh Tuan Nguyen J. P., 2020), (Piche, 2020), (Teng An, 2017). It is important to note that hydrogen-induced fatigue failure is a time-dependent phenomenon; hence, integrity programs may need to be modified accordingly for hydrogen-blended natural gas operation.

2.1.5 Effect on Plastic Materials

Hydrogen is generally compatible with most polymeric material. [redacted] Though chemically inert to polymer, hydrogen can influence polymer properties at high pressures due to a plasticizing effect (Barth, Simmons, & San Marchi, 2013). The primary concerns with the effects of natural gas or hydrogen on the properties of PE are different compared to metals. [redacted]

[redacted]

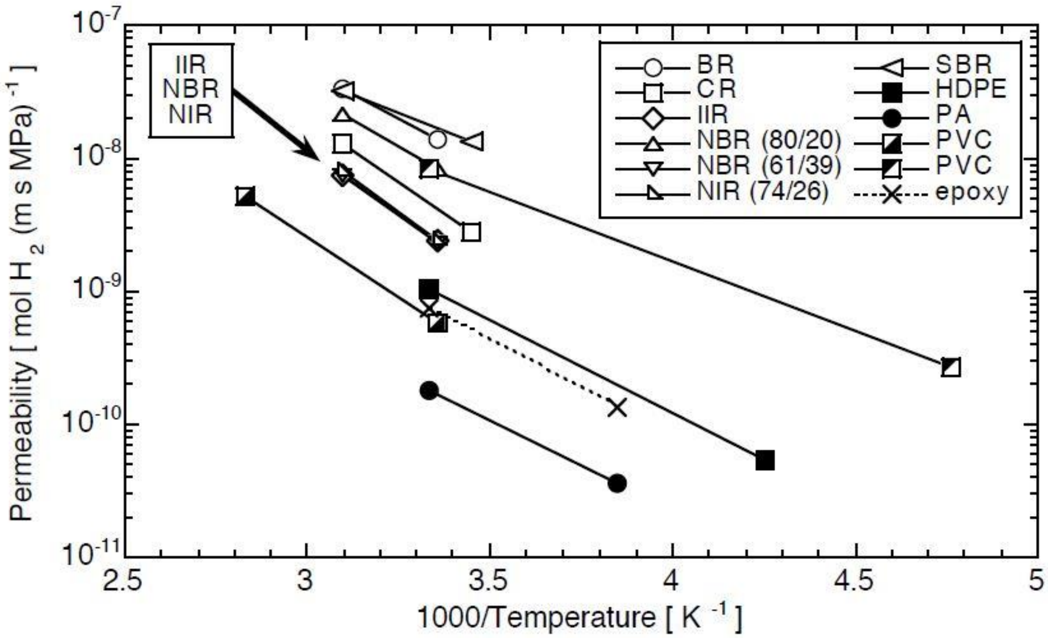
[redacted]

- Hydrogen does not show any significant effect on the tensile properties of PE pipe; however, elevated temperature and pressure may induce plasticizing effects followed by modified mechanical properties. Note that hydrogen does not cause embrittlement of PE pipes like metals as hydrogen does not dissociate at the PE surface like it is known to do in metals. In summary, hydrogen is inert to PE pipes; however, the effects of hydrogen on PE materials at high temperatures and pressures require further investigation (ASTM International, 2021).

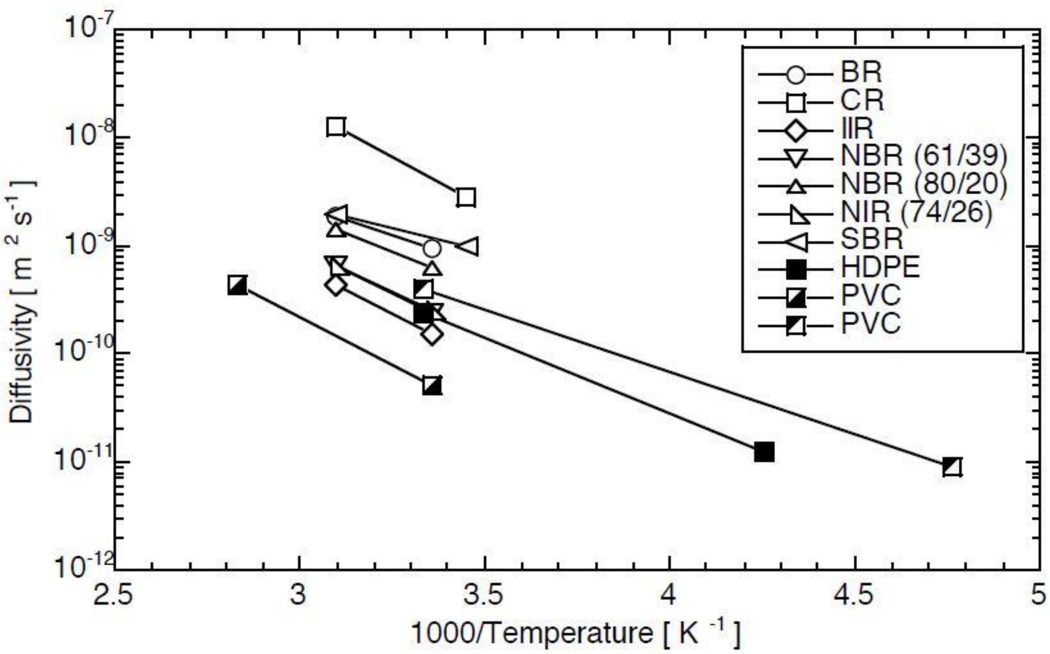
[redacted]The melting, softening, and glass-transition temperature of polymers are affected by the operating pressure and temperature of the system. Operating pressure and temperature in hydrogen service need to be carefully monitored (ASTM International, 2021); [redacted]

- It is reported that the tensile properties of polymers are affected by the operating pressure and the temperature of the service environment; however, recent studies suggested hydrogen does not exhibit any significant effect on the tensile properties of PE pipe up to 10 MPa pressure after a long period of hydrogen exposure (Castagnet, 2010), (Sylvie Castagnet, 2012), (S. Castagnet, 2011).

- Hydrogen can slowly move through polymers and can be characterized by two thermodynamic properties: diffusivity and solubility. Diffusivity indicates the movement rate of hydrogen through the material, and solubility describes the amount of hydrogen contained within the material. Permeability is the product of these two properties. The solubility of hydrogen in PE is very low. Though diffusivity and permeability are also low, it is affected significantly by increasing temperature and pressure. Both properties exhibit a higher permeation rate with increasing temperature. Due to the relatively low solubility of hydrogen in polymers, fracture toughness and fatigue failure do not pose a significant concern for PE materials in blended hydrogen service. The effect of temperature on permeability and diffusivity is presented in Figure 2-9:



(a)



(b)

Figure 2-9 Temperature dependence of hydrogen (a) permeability, and (b) diffusivity of several polymer materials (Amerongen, 1951).

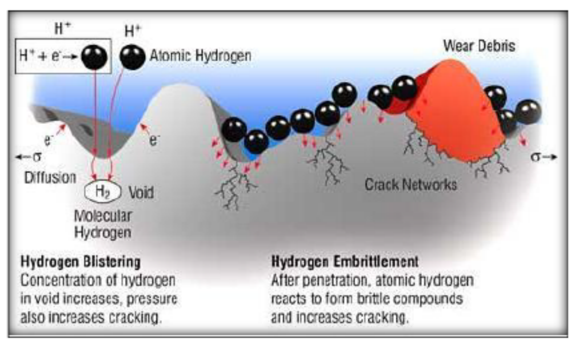
Failure Mechanisms & Modes

Based on the above discussion on metallic and plastic materials, some of the concerns are summarized in this section:

3.1 Hydrogen Embrittlement of Steel

Hydrogen embrittlement is one of the most significant challenges for steel in hydrogen service; however, there is no unanimously accepted mechanism to explain hydrogen embrittlement (Piche, 2020), (J. Song, 2014). The embrittlement mechanism is theorized to primarily depend on hydrogen-trapping sites which include defects, dislocations, vacancies, inclusions, precipitates, grain boundaries, alloying elements, interfaces etc. Hydrogen atoms (ions) may permeate through the steel structure under various environments such as hydrogen gas, moist air, sour gas, water and/or acidic solutions. These atoms are then trapped in these sites and eventually cause degradation known as hydrogen embrittlement (Wan, 2019). A high-level summary of the embrittlement mechanism is given below:

- Hydrogen adsorption and dissociation occur on fresh metal surfaces, which can likely be created as a crack grows.
- Accumulation of hydrogen gas in the sub-surface void or cavity can form blisters due to increasing partial pressure of hydrogen.
- Stepwise internal cracks may connect adjacent hydrogen blisters on different planes in the metal or to the metal surface. This is also known as stepwise cracking.
- The presence of surface films, scales and inhibitive gaseous species such as oxygen, carbon monoxide, etc., can interfere with the process.



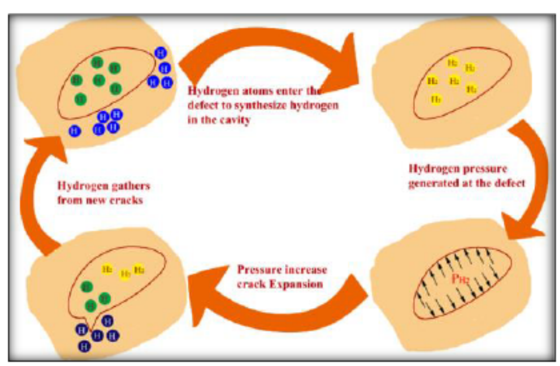


Fig-7.1: Schematic for hydrogen embrittlement process (Zhang, 2020), (The Metallurgy's Blog for Beginners, 2022).

Though no single mechanism can explain the embrittlement phenomenon universally, the combination of different mechanisms is used to explain hydrogen embrittlement for each specific scenario. Current postulated mechanisms are discussed below:

3.1.1 Hydrogen-Enhanced Decohesion (HEDE) Model

According to the hydrogen-enhanced decohesion (HEDE) theory, H^+ atoms gather at locations of high triaxial stress and lead to weakening of bonds of metal atoms followed by fracture. The hydrogen atoms segregate at the grain interface and weaken the metal-metal bond leading to decohesion. When the applied stress is greater than the cohesive strength along with the interface, cracks initiate in the matrix or existing cracks start to propagate. This model is categorized as a smooth brittle fracture with limited plasticity (Piche, 2020).

3.1.2 Hydrogen-Enhanced Localized Plasticity (HELP) Model

The hydrogen-enhanced localized plasticity (HELP) model suggests that the hydrogen atom attached to existing dislocations inside the metal reduces interferences for dislocation movement. The moving dislocations enhance localized plasticity of the material which gives rise to the name hydrogen-enhanced localized plasticity. The coalescence of these moving dislocations initiates cracks or favours the propagation of an existing crack. (Piche, 2020).

3.1.3 Adsorption-Induced Dislocation Emission (AIDE) Model

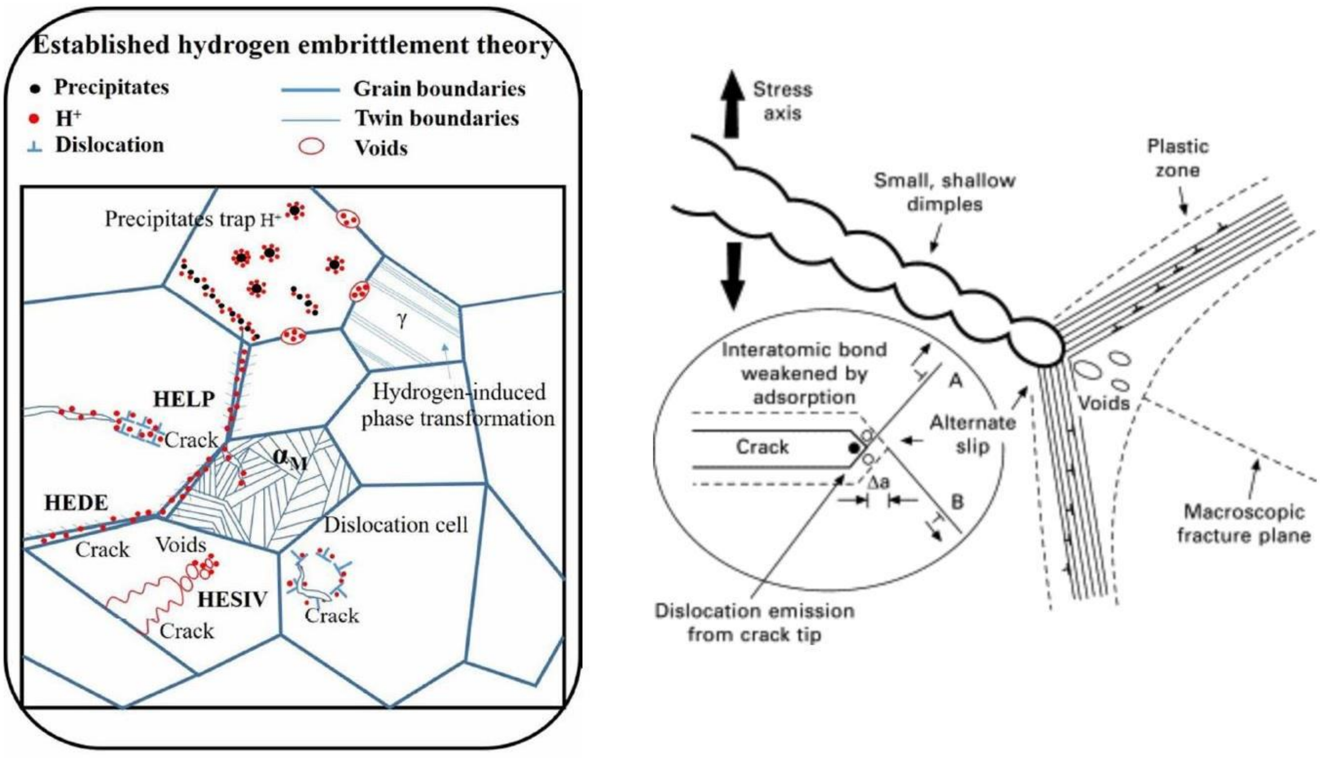
In this mechanism, hydrogen adsorption causes weakening of the interatomic bonds over several atomic distances. This process involves the following:

(i) Nucleation and increasing movement of dislocations away from the crack tip

(ii) Nucleation and propagation of micro-voids

Void formation contributes to crack growth, resharpens the crack tip opening angle, and increases crack growth (Lynch, 2012).

Figure 3-1 explains the HEDE, HELP and AIDE embrittlement mechanisms.



(a) (b)

Figure 3-1 Hydrogen embrittlement mechanism (a) HEDE and HELP, (b) AIDE (Lynch, 2012)

3.2 Fatigue Crack Growth in Steel

Material failure under cyclic loading at lower stress than the tensile strength of a material is known as fatigue. Fatigue is a concern in steel pipelines transporting natural gas due to pressure fluctuations. Studies suggest that fatigue could be the most probable cause for failure of a pipeline carrying hydrogen-NG blended gas (Bo Meng, 2017), (Mohsen Dadfarnia, 2019). Fatigue failure is primarily associated with nucleation and growth of microcracks until a final, unstable fracture. Fatigue crack growth rate includes three distinguishable regimes which are:

Stage I – threshold regime

Stage II – Paris regime

Stage III – final fracture

Stage I corresponds to the formation of a crack at a particular stress intensity factor (ΔK). Crack growth is not visible if ΔK is less than the threshold value, ΔK_{th}.

Stage II exhibits a moderate fatigue-crack growth rate (Huan Li, 2018) and can be described by the following equation known as the Paris law (the most extensively used model for predicting fatigue crack growth) (Huan Li, 2018):

$$\frac{da}{dN} = C(\Delta K)m$$

Where,

$\frac{da}{dN}$ = crack growth per cycle

ΔK = stress intensity factor

C & m = material coefficients, obtained experimentally

Stage III corresponds to an accelerated crack growth rate and ultimate failure by rupture (Huan Li, 2018).

The crack growth rate of the three different stages is illustrated by the following figure:

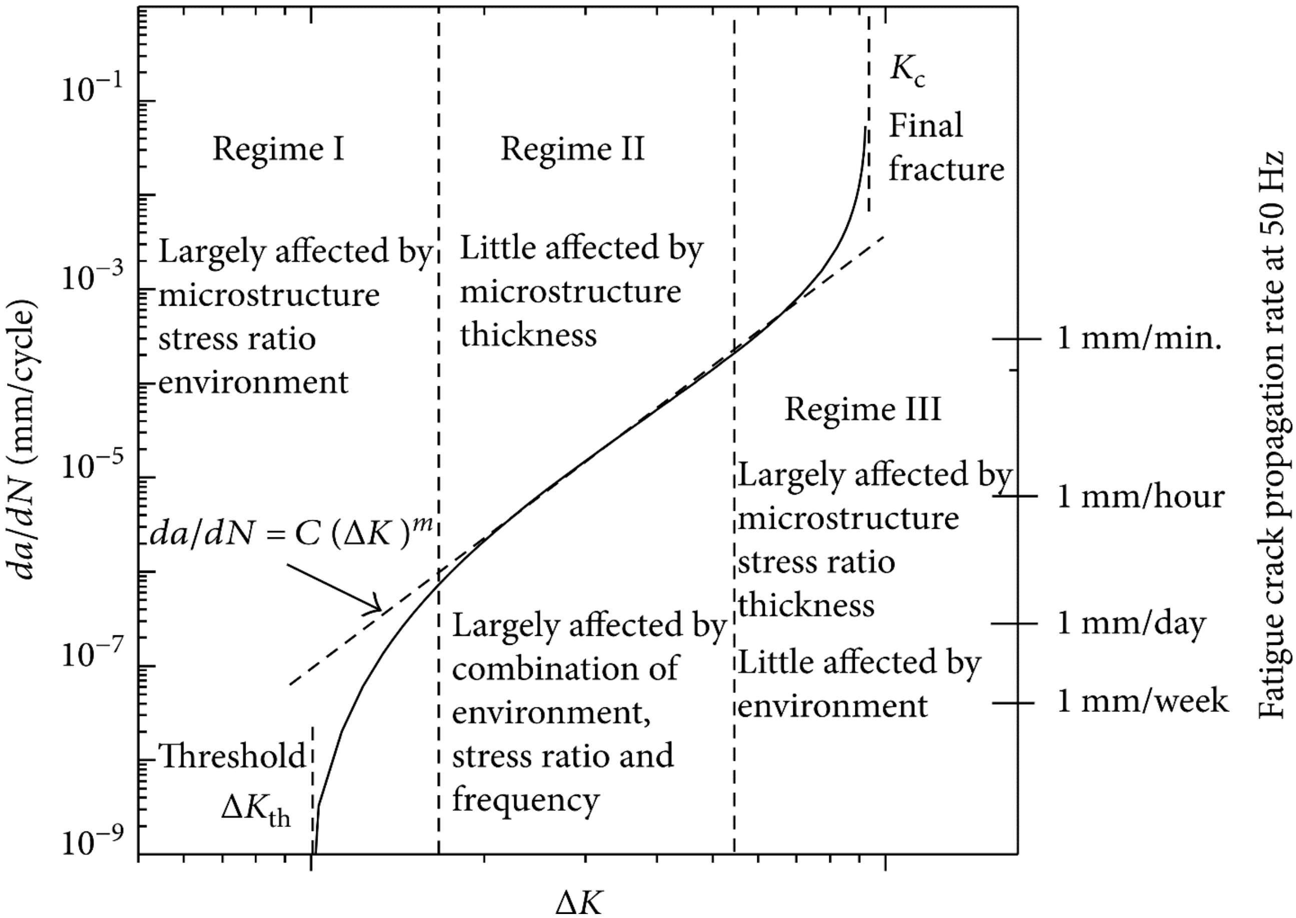


Figure 3-2 Typical regimes for fatigue-crack growth rate as a function of the stress intensity factor for metallic materials (Huan Li, 2018).

Hydrogen reduces fracture toughness of steel and enhances the crack propagation rate. The presence of hydrogen increases the brittle area of the metal matrix and makes it vulnerable to fatigue failure; hence, susceptibility and resistance to fatigue for affected material need to be carefully assessed before incorporating hydrogen into a system.

3.3 Corrosion

Corrosion is the degradation of metal due to an electrochemical reaction with the surrounding environment. This deterioration mode gradually creates metal loss by oxidation creating rust. The loss of material reduces the strength of the material and may cause failure in certain conditions – typically in the form of leaks. When corrosion occurs on the internal surface of a pipe, it is referred to as internal corrosion and results in localized metal loss to the inner pipe wall. The material loss can eventually develop into pinholes that fail by leakage or rupture. If this damage is left untreated, the pipe may become more susceptible to overpressure events, geological variations, and external stresses (Pipeline & Hazardous Materials Safety Administration, 2018). Corrosion reactions are a source for generating a hydrogen ion which can easily permeate through the pipe wall. This hydrogen ion then combines to create molecular hydrogen (H_2), and in doing so, the reaction creates localized pressures and stresses that may provide a preferential site for crack formation, initiation and growth. Corrosion defects such as cracks, pits, etc., provide entrapment sites for hydrogen and increase the localized concentration of hydrogen and may eventually lead to brittle fracture (Wenyao Li, 2021).

3.4 Leakage Rate through Materials

Though PE pipe is inert to hydrogen, a concern is the permeation of hydrogen through pipe bodies, seals, and connections. The smaller kinetic diameter of hydrogen (2.89 Å) compared to methane (3.80 Å) results in increased permeation rates for hydrogen compared to methane. For example, one study measured approximately double the permeation coefficient value for hydrogen (127 ml mm m-2 bara-1 day-1) compared to methane (56 ml mm m-2 bara-1 day-1) (Kim Domptail, 2020). NaturalHy & NREL technical assessment reported a four to five times higher permeation rate of hydrogen through PE pipes compared to methane. Another study reported a similar leakage rate (Dries Haeseldonckx, 2007). It is important to note that though the permeation coefficient of most sealing materials is higher than the PE pipe body, the leakage rate is higher through pipe body due to the large surface area; however, permeation decreases with increasing PE density and reduced operating pressure. Hence, HDPE pipes are expected to exhibit lower permeation compared to MDPE pipes (no reference testing data available).

A calculation for the Dutch pipeline system suggested an approximately 0.00005% leakage rate for a 17% hydrogen-blended natural gas distribution system. The study used an experimentally derived modified permeation coefficient (M. W. Melaina, 2013).Another study reported a 0.00005-0.001% leakage rate of the total transported volume (Dries Haeseldonckx, 2007). NaturalHy concluded that 30% hydrogen can be added to low-pressure systems without significantly increasing leakage risk or requiring additional mitigation measures (M. Schmidt, 2019). An NREL simulation computed that a 20% hydrogen blend within the approximately 415,000 miles of PE pipes in the United States would result in a gas loss of about 43 million ft3/ year, with about 60% of the losses being hydrogen and 40% being natural gas. The estimated volumetric loss is approximately double compared to 100% natural gas transportation.

Leakage rate through the pipe body for steel pipe is not a significant concern. A recent study reported the leakage rate of NG, H2, and NG-H2 blended gas is almost identical for a low-pressure system. However, the odorant used for NG may not be sufficient to detect H2 leaks due to the lower molecular weight of hydrogen (Alejandra Hormaza Mejia, 2020).

Another study at SoCalGas facilities (simulated leak environment) on leakage rate shows that the leakage rate is almost identical at lower gauge pressure. Figure 3-3 shows the summary of that experiment:

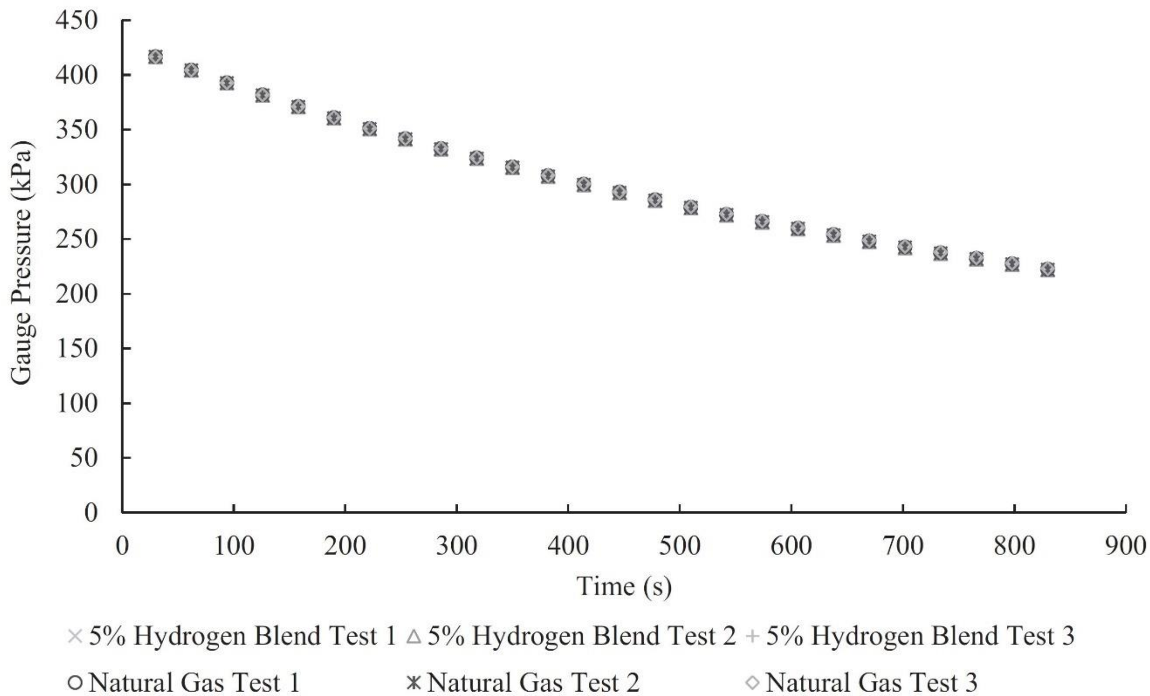


Figure 3-3 Leak down test at 471 KPa (68.3 PSI) (Alejandra Hormaza Mejia, 2020)

For steel pipes, Austin R. Baird et. al concluded that at lower pressure and with lower hydrogen concentration, the leakage rate is similar for both pure hydrogen & natural gas; however, with increasing hydrogen concentration, the total volumetric leakage rate increases indicating hydrogen exhibits a higher leak rate compared to natural gas (Austin R. Baird, 2021). The volumetric outflow (leakage) rate of pure or blended hydrogen from polymeric materials or mechanical connections is dependent on factors such as material permeability, internal operating pressure, hydrogen partial pressure, temperature, joint tightness, etc.

Blended Gas Characteristics

Natural gas and hydrogen have significant differences in terms of gas properties. Typical natural gas composition is usually mostly methane and a smaller amount of ethane, propane and butane along with other trace constituents. A small amount of other higher-order hydrocarbons and gases may also be present depending on the source of the natural gas. The molecular mass and heating value of these gases are higher than hydrogen; hence, hydrogen-blended natural gas exhibits different characteristics from natural gas based on the blend ratio and environmental conditions. The differences are discussed below:

4.1 Natural Gas and Hydrogen Gas Comparison

Methane (CH4) is the primary component of natural gas with a lower concentration of other heavier hydrocarbons and few non-hydrocarbon gases. The purity of hydrogen will differ depending on the production source. The following table exhibits gas properties under ambient environmental conditions for pure methane and pure hydrogen gas:

Table 3 **Hydrogen and Natural Gas Properties at Ambient Conditions Property Hydrogen Methane** (Austin R. Baird, 2021)

Property	Hydrogen	Methane
Molecular Weight (g/mol) [8]	2.016	16.043
Buoyancy (ratio to air)	0.07	0.54
Density (kg/m^3) [9] [10]	0.0899 ~14 times lighter than air	0.668 ~1.8 times lighter than air
Dynamic Viscosity @ 20°C (10-5 Pa-s) [11]	0.88	1.1
Flammability Limits (vol. %) [10]	4-74	5.3-15
Stoichiometric Concentration in Air (vol. %) [10]	29	9
Maximum laminar burning velocity (m/s) [10]	3.25	0.44
Relative radiative heat transfer (%) [10]	5-10	10-33
Diffusion Coefficient @ 20°C (cm^2/s) [12]	0.756	0.21
Gross Heating Value (kJ/m^3) [13]	12,109	37,669

One significant difference to note is the gross heating value of hydrogen is approximately one-third of natural gas. Conversely, diffusivity and burning velocity are significantly higher. The probable effect of these differences on the system is discussed in the prior sections. [redacted]

4.2 Temperature Profile

Research shows that the temperature profile of gas in a buried pipeline system varies throughout the pipe length. The temperature profile is also significantly affected by seasonal variability in ground temperature. Given previously suggested relationships between outflow rate and temperature, leakage behaviour will be different and inhomogeneous for a blended gas as hydrogen is much lighter compared to natural gas. Mohsen et. al studied the temperature profile of a buried pipeline, and their results are presented in Figure 4-1 (Austin R. Baird, 2021).

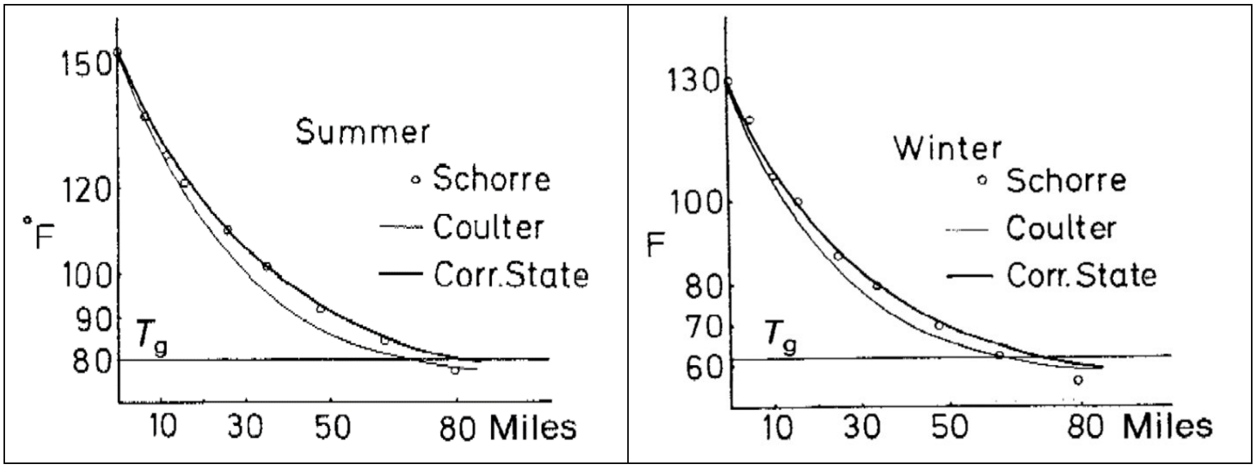


Figure 4-1 Pipeline temperature profile vs distance for summer and winter (Austin R. Baird, 2021).

A difference in temperature may arise for long sections of pipeline due to heat transfer with the surrounding soil, depth in relation to the frost line, and presence of heat sources (compressor, heaters, etc.); this could lead to a non-uniform permeation rate within a piping system. This effect could be more pronounced with a higher %H2 blend (partial pressure) and increasing pipe length.

4.3 Dispersion Behaviour of Hydrogen and Methane

The molecular weight of hydrogen is lighter than methane. As a result, hydrogen has a higher dispersion rate than methane. Research has been conducted to study the dispersion characteristics of blended hydrogen-natural gas mixtures in air. In one study, researchers used a 25 m^3 enclosed test cell to represent an enclosed room and added sensors in several locations to measure the localized H_2 and CH_4 composition. Figure 4-2 shows the test cell and sensor positions.

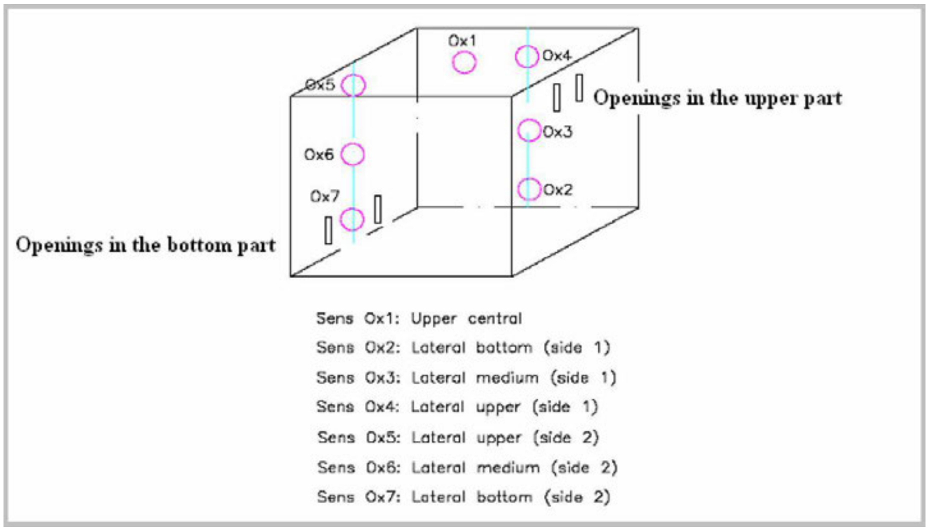
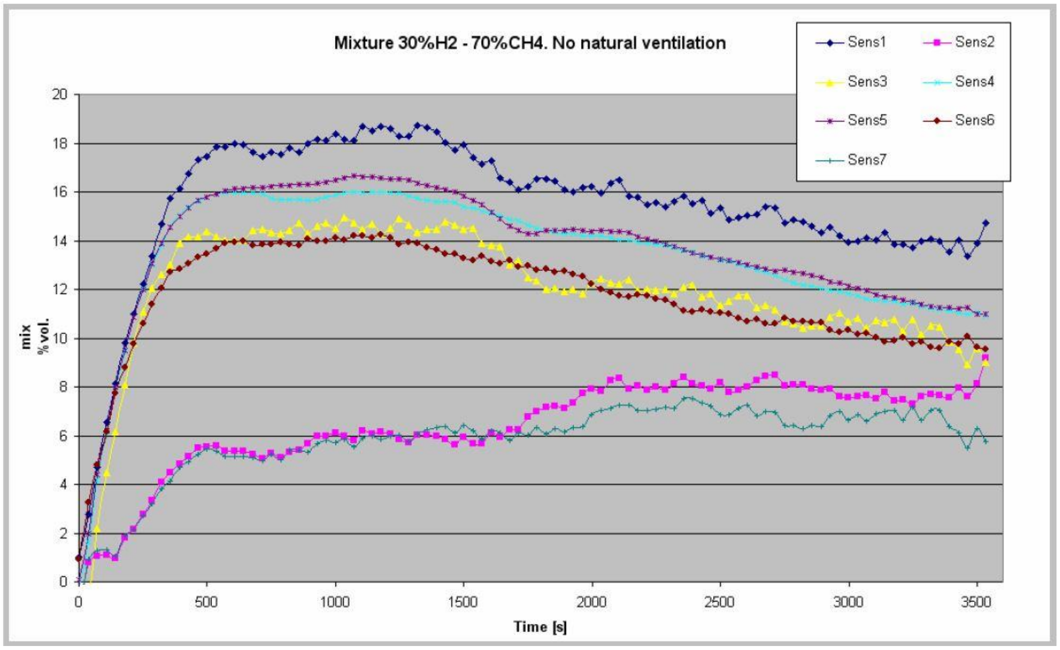


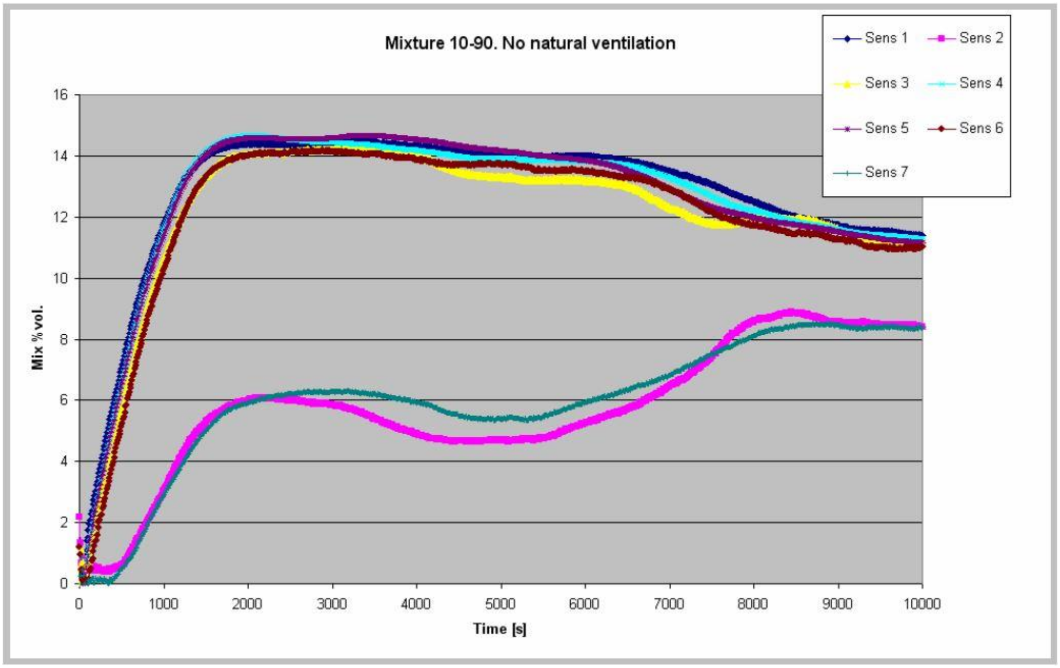
Figure 4-2 Gas dispersion analysis test cells with sensor positions (Marangon, 2014)

The study tested two different blended gas mixtures: (i) 30% H_2+70% CH_4, (ii) 10% H_2+90% CH_4 that showed different dispersion behaviour based on the hydrogen to methane ratio. The top section of the enclosure revealed higher hydrogen gas concentration compared to the bottom portion of the test cell.

In brief, the blended gas composition was not found to be homogeneous throughout the test cell due to the different dispersion behaviour of H_2 and CH_4 (Marangon, 2014). The probable reason may be the faster vertical movement of the blended gas with higher %H_2 compared to methane (Austin R. Baird, 2021). Figure 4-3 shows the gas composition (%H_2) found at different sensors in the cell.



(a)



(b)

Figure 4-3 The %H_2 reading at different sensors of the test cell (a) 30% H_2+70% CH_4, (b) 10% H_2+90% CH_4 (Marangon, 2014)

Dispersion characteristics are not independent but can vary with many factors such as temperature (Austin R. Baird, 2021), leak size, pressure, ambient conditions and ventilation.

4.4 Risk Assessments

Global interest in hydrogen and hydrogen blending as a green energy carrier has led to a multitude of research, pilot projects and studies on material impacts, safety and risk topics.

This section presents some of those findings available publicly at the time of writing.

Safety risks of transporting gaseous hydrogen are generally comparable to those of natural gas. Hydrogen is lighter than air and natural gas so it rises and disperses faster than methane when released into the atmosphere. Hydrogen's explosive range is between 4% (LEL) and 75% (UEL) which is much wider than natural gas (5-15%) so hydrogen needs much less air to burn. Hydrogen burns quickly back to the source and a hydrogen fire will radiate significantly less heat than methane – posing less risk of thermal damage or secondary fires away from the point of combustion. [redacted] HYREADY also presents risk assessment results from the NaturalHy project using a proprietary risk assessment software called LURAP. In the example provided, risk is found to be slightly higher with a 25% hydrogen blend rate compared to the base case of 0% blending. It is interesting to note that the risk is reduced at increased distance from the pipeline as a result of the reduced hazardous region from higher blends of hydrogen. Hyready suggests that the increase in individual risk due to blends of up to 20% compared to a natural gas base case are minimal.

Codes, Standards, Policies and Regulations

There are many projects focusing on hydrogen blending with natural gas around the globe; however, there is a lack of comprehensive standards, long-term policies, and a consistent regulatory framework in Canada in contrast to long-established natural gas transportation. The existing policies are not consistent across regions, and some projects may require a patch-work approach that slows down the design, approvals and implementation process. The absence of policies and regulations may act as a barrier to achieving the 2050 net-zero goals for the energy sector. It is important to note that hydrogen is a new and developing sector in Canada. Hence, existing codes and standards may not adequately address the needs of proposed and existing hydrogen blending initiatives. More cohesive national and provincial codes, standards, policies, and regulations are needed to support hydrogen blending as a means of decarbonizing the energy sector.

[redacted]

5.2 Financial

There are several financial challenges involved with the introduction of hydrogen energy. The next challenge is technological barriers. Existing pipelines and assets were designed for natural gas transportation. [redacted] Hence more research work and innovation are needed to advance this technology to meet the 2050 target.

Financial challenges can be divided into two parts: (i) economic challenges and (ii) technological challenges.

[redacted]

[redacted]

Recent Development & Capabilities

The existing natural gas distribution network includes pipelines, station equipment and end-user equipment that were designed to transport natural gas. Hence, the compatibility of these assets needs to be assessed before adding hydrogen.

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

6.1 Pipeline Network

- **Steel**
  - **Pipe body**

[redacted] Based on previous discussions, no significant change in tensile properties (YS, UTS, etc.) is expected due to the addition of hydrogen; however, lower fracture toughness, reduction of area at fracture zone, and increasing rate of fatigue crack growth are potential concerns [redacted] (San Marchi, 2012), (Pluvinage, 2021), (Boot T, 2021). Higher MOPs may permit propagation of existing cracks followed by material failure. The partial pressure of hydrogen is one of the governing factors for hydrogen diffusion and embrittlement. The partial pressure of hydrogen increases with increasing operating pressure and blend percentage (Kim Domptail, 2020). Another effect of hydrogen on carbon steel is the modification of the fracture mechanism. Blended gas (hydrogen & NG) causes two potentially active fracture mechanisms: ductile and quasi-cleavage (brittle) fractures (Thanh Tuan Nguyen N. T., 2020), (Boot T, 2021). Brittle fractures and the number of crack initiation sites increase with higher hydrogen concentration and increase the risk for failure.

[redacted]

[redacted]

- **Weld zone**

Recent studies exhibit that hydrogen concentration and exposure time do not affect the YS and UTS of the weld; however, Vickers hardness slightly increased (5-20%) in the near-surface area due to the presence of hydrogen (San Marchi, 2012). Hydrogen-enhanced fatigue may lead to failure due to the accelerated growth of existing crack-like defects in the welds (Kim Domptail, 2020). One recent study suggested that weld metal is less susceptible to hydrogen embrittlement than body metal (BM) due to refined grain size and higher toughness achieved by post-weld heat-treatment (Boot T, 2021).

[redacted] CW pipes have better homogeneous grain distribution throughout the pipe matrix; hence, mechanical properties are expected to be more homogeneous (weld zone and BM) (Rucker, 2015). LF and HF ERW process differences are mostly related to HAZ width and hardness change (Palkovic, 2019), (MANAGING PIPELINE THREATS, 2022). DSAW welding process uses filler materials and has wider WMZ and HAZ.

A recent study shows that hydrogen-blended natural gas significantly reduces %RA at the weld zone during the notch tensile test (50%-70%). In addition,

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[redacted]

hydrogen lowers the tensile strength of the weld material by less than 15%. And the ERW welding zone shows the lowest reduction of area values (12-20%).

Due to hydrogen addition, fracture toughness of the weld zone may be significantly reduced at the HAZ; however, fatigue crack growth rate (parent metal and weld zone) was reported to be unchanged for X60 steel at 1000 psi (Michler T, 2021).

[redacted]

Note that increased density of dislocations and voids make the material more susceptible to embrittlement (Boot T, 2021). Hence, repaired pipe areas may have vulnerable spots for preferentially higher concentration of hydrogen.

- [redacted]

- **Stainless Steel**

  Hydrogen compatibility of stainless steel depends on the steel type. Austenitic & ferritic stainless steel has enhanced hydrogen transportation capability; however, martensitic stainless steel is susceptible to hydrogen-assisted cracking. The type of stainless steel needs to be identified and replaced as needed. Sandia laboratory published a set of test data performed on different types of stainless steel (Michler T, 2021).

- **Copper Tubing**

  The permeability, diffusivity, and solubility of hydrogen in copper are very low. Hence copper tubing is expected to be relatively unaffected by high-pressure hydrogen gas (San Marchi, 2012); [redacted] While copper itself is considered compatible with hydrogen, its associated mechanical transition fitting may warrant review due to increased leakage risk.

- **Polyethylene**

  Hydrogen does not exhibit any significant effect on the integrity of PE as it is inert to hydrogen (Kim Domptail, 2020), (Jeroen Wassenaar, 2020).The primary concern with plastic is the permeation of hydrogen through pipe bodies, seals, and connections.

- **Valves**

  [redacted] While the body of the valves themselves are not expected to fail, there could be an increased leakage rate due to permeability through elastomers, leakage through mechanical joints, or eventual failure of sealing elements.

- **Soft goods and other component**

  Soft goods [redacted] are polymeric materials and do not chemically interact with hydrogen; hence, change in mechanical properties or hydrogen-assisted cracking is not a concern. Conversely, friction and wear, rapid gas decompression, plasticization at higher pressure and H_2 concentration, transport properties, contaminants effect, etc. require further understanding (Michler T, 2021). Based on published literature, the hydrogen blending tolerance of polymeric materials is 20-30%. It could be increased after existing asset testing and evaluation of the results (Gallon, 2020), (Kim Domptail, 2020). Table 4 & 5 shows the AIGA/EIGA guidelines for hydrogen compatibility of elastomers and NREL reports on various polymeric materials.

Table 4 Elastomers Compatibility with Hydrogen (EIGA, 2014)

Material	Compatibility
Natural Rubber	Fair
Butyl Rubber	Good
Silicone Rubber	Fair
Neoprene ®	Good
Buna S ®	Good
Hypalon ®	Good
Viton ®	Good
Buna N ®	Good

Table 5 Polymeric Material Compatibility with Hydrogen (M. W. Melaina, 2013)

Polymers	Compatibility
Polyethylene	Good
Polyvinyl Chloride	Good
Natural Rubber	Fair
Butyl Rubber	Good
Silicone Rubber	Fair
Neoprene (CR)	Good
Viton	Good
Buna N (NBR)	Good

Components such as couplings, tubing, flanges, plugs, bushings, etc. are made of combinations of brass, copper, forged steel, cast iron, etc. As discussed in prior sections, some of these materials may not be ideal for hydrogen service. The failure risk of these components depends on the degree of hydrogen exposure and stresses in the material. If the component is covered with polymeric seals or gaskets, or not directly exposed to hydrogen gas, the risk is minimal; however, direct hydrogen exposure increases the risk of hydrogen-assisted cracking in metals. Polymeric components are not as vulnerable as steel since polymers are inert to hydrogen.

6.2 Station and Network Equipment

[redacted]

- **Meters**

  Different types of meters have different capabilities; however, lack of testing data is the reason for not having a clear understanding on the hydrogen compatibility of existing meters. [redacted] The accuracy of measurement with Coriolis meters is not expected to be impacted with hydrogen admixing; however, there is no available test data to confirm this (Joan Ogden, 2018). [redacted] A recent study reported that for the tested gas meters, no significant metrological difference was found between the obtained average drift of errors of indications after the durability test using natural gas mixtures with different hydrogen concentration (from 0% to 15%). The study notes that prolonged operation of gas meters in hydrogen service may result in deterioration of internal components (i.e. reduced durability, which may result in eventual measurement errors. (Government of Ontario, 2020). Ultrasonic meters are considered to be sufficiently accurate at less than 10% by volume hydrogen. At 10-30% by volume hydrogen, the meter may no longer accurately detect the ultrasonic pulses if maximum calibrated flow for the gas mixture is exceeded; slight deviation due to changed sound velocity and limited resolution of measurement [redacted] policy to suggest that metering up to 5 vol% hydrogen will not require any material changes, while any blends above 5% will require a coordinated calibration and certification effort between the operator and Measurement Canada.

- **Pressure Vessels (Filters, tanks, etc.)**

  [redacted] Pressure vessel compatibility will depend on the original design, material selection and construction parameters. The existing ASME VIII Div I or similar standards cover the requirements for hydrogen-retaining vessels.

- **Odourant** (MARCOGAZ, 2021)

  The composition and physical properties of natural gas may change by adding hydrogen and therefore warrant a review of currently available odourants. A study by MARCOGAZ raised the following concerns:

  - Chemical reaction: Sulphur-based odourant, such as THT, mercaptans, etc., does not negatively react with hydrogen in the gas distribution system environment; however, sulphur-based odourant should be avoided for fuel cell applications where high-purity hydrogen is needed.
  - Physical effect: The odourant should be selected based on the physical and environmental characteristics of the blended gas. For example, odourants with lower density and higher vapour pressure could be a better fit for higher amounts

of hydrogen in the H_2-NG mixture. It is particularly significant when a blended odourant (mixture of two or more different odourants) is used. Another concern is meeting the regulatory requirements for odourants used in natural gas distribution systems. Based on current European regulations, natural gas should be readily detectable by odour at a concentration of 20-25% of the LEL. Since the LELs of hydrogen and natural gas are very similar, it is not expected to be an issue for blended gas.

- Odourant masking: There is no significant evidence found on this issue.
- Odourant measurement: No measurement issues were reported for gas chromatograph applications; however, odourant measurement using chemical sensors might be affected due to the presence of hydrogen.

In Germany, several hydrogen blending projects use THT, mercaptan, TBM, and mixtures thereof as odourants, and no significant issues were reported thus far. The German National Committee indicated that odourants specified in ISO 13734 should work for hydrogen-NG blended mixtures. In Italy, a confidential study showed that mercaptans worked without any reported issues with historical manufactured gas, which had approximately 28-50% hydrogen. In the Netherlands, DNV and SGS Nederland tested three different types of odourants (THT, Spotleak 1001® (TBM+DMS 80:20), and Gasodor® S-Free) on different blended hydrogen gas compositions and pure hydrogen. Their analysis showed no significant effects on the odourant system due to the addition of hydrogen. Hence, the study indicates tested odourants can be used for blended gases and pure hydrogen. In England, Hy4Heat tested five odourants and concluded all are fit to use in a 100% hydrogen gas distribution grid for combustion applications; however, further evaluation is required for use in fuel cells and fuel cell vehicles (Arul Murugan, 2020). The composition of the odourants and their testing results are summarized in the tables below:

Table 6 Tested odourant and their compositions (MARCOGAZ, 2021)

Odourant name (including alternative names)	Compound	Rationale
Odourant NB, NB	78% 2-methyl-propanethiol, 22% dimethyl Sulphide	Primary odourant used by Scotia Gas Network and other UK gas networks
Standby Odourant 2, NB Dilute	34% Odorant NB, 64% Hexane	Diluted form of Odorant NB used by SGN if supply of Odorant NB is compromised
Odourant THT, THT	100% tetrahydrothiophene	Most commonly used odourant within European gas networks
GASODOR-S-FREE, Acrylates	37.4% ethyl acrylate, 60.1% methyl acrylate, 2.5% 2-ethyl-3methylpyrazine	Sulphur-free gas odourant in use within some German gas networks
5-ethylidene-2-norbornene, Norbornene	5-ethylidene-2-norbornene	Odourant with an unpleasant odour that is suitable for fuel cell applications

Table 7 Research summary of the tested odourants (MARCOGAZ, 2021)

Section	Odorant NB	Standby odorant 2	Odorant THT	GASODOR-SFREE	5-ethylidene 2-norbornene
Health/environment					
Olfactory					
Pipeline					
Flame boiler					
Fuel cell					
Economic (*)					

(*) Note: the economic evaluation is specific to the UK and should not be extrapolated to foreign jurisdictions.

The MARCOGAZ study concludes that more information is needed on the following sections for odourants in hydrogen service:

- Effect of odourization on the physical properties of the blended gas and odourant
- Effect of modified chemical properties between hydrogen and odourants at high (non-distribution) pressures

- Effect of higher hydrogen concentration on odourant (up to 100%)
- Effect of impurities from hydrogen production

MARCOGAZ identified a potential issue for higher hydrogen concentration blends. As hydrogen and natural gas have different physical properties (primarily molecular weight), their velocities will not be equal. This may result in gas separation such that odourant distribution could be inhomogeneous in a leak. MARCOGAZ suggested using a maximum of 15% H_2 for blended gas with currently available odourants to address this concern. The limit may increase based on further testing and data analysis (MARCOGAZ, 2021). A study for the sun underground storage project which measured stagnant blended gas over the course of a year suggested that no material separation of the mixture was found. DBI-GUT (HyReady, 2022) has also suggested that decades of odourized service in manufactured gas systems has not revealed any indications of significant separation of hydrogen from methane in the gas stream. Ultimately, additional research is warranted to validate these findings.

6.3 End-User Equipment

[redacted] The hydrogen blending capability is presented by colour-coding, and the following chart explains the colour code and capability relationship.

(green)	**Largely compatible**
(yellow)	**Possibly compatible; depends on vintage, manufacturer, type, etc.**
(orange)	**Possibly compatible; research phase**
(red)	**Currently incompatible; research on-going**

[redacted]

Existing and Upcoming Hydrogen Projects

There are many hydrogen projects proposed, in development or operational around the world. This section presents a high-level summary of known projects. As this is a rapidly evolving field, this should not be construed as a complete listing of all hydrogen-related projects.

7.1 Projects Around the Globe

The following table shows some of the known hydrogen projects announced since 2015. The data were collected from the IEA database.

Table 9 List of hydrogen pilot projects around the world collected from the IEA database (IEA , 2019)

Project name	Country	Start	End	Technology	End-use fuel or feedstock - Sector									Quoted installed capacity			IEA estimated normalized capacity [nm^3 H_2/hour]
					H - Power	H - Grids	H - Mobility	H - Industry	H - CHP	H - Chemicals	M - Grids	M - Mobility	L - Mobility	MWel	nm^3 H_2/hour	Tonne CO_2 captures/yr	
Quest	Canada	2015		Fossil				1								1000000	141089.17
Raglan Nickel mine	Canada	2015	2020	ALK	1									0.32			75
MeGa-stoRE Optimising and Upscaling	Denmark	2015	2018	ALK							1	1	1	0.25			59.52
SYNFUEL	Denmark	2015	2019	SOEC									1				
Port Jerome	France	2015		Fossil				1								100000	14108.92
Energiepark Mainz	Germany	2015	2017	PEM		1	1	1						6	1000		1000
H2ORIZON	Germany	2015	2017	PEM	1		1		1					0.9	70		70
Hamburg - Schnackenburgallee	Germany	2015		PEM			1							0.19	30		30
Reussenköge	Germany	2015		PEM	1		1		1	1				0.02	4		4
Dresden	Germany	2015		SOEC	1									0.01			2.78
Emden II Upscaling	Germany	2015	2020	PEM	1				1		1						
RegEnKibo, Kirchheimbolanden	Germany	2015	2018	Unknown PtX							1						

Gwalpahari Solar-Hydrogen demonstration	India	2015		Unknown PtX	1		1							0.12			26.67
SmartFuel hydrogen station	India	2015		Unknown PtX			1										
Higashi-Ogishima-Naga-Park	Japan	2015		PEM	1										1		1
Regio Energie Solothurn/Aarmat hybrid plant	Switzerland	2015		PEM		1					1			0.35	60		60
Pilot & Demo PtM HSR	Switzerland	2015	2017	ALK							1	1		0.03			5.95
Rapperswil	Switzerland	2015	2017	Unknown PtX							1	1					
Aberdeen, Hydrogen bus project	United Kingdom	2015	2018	ALK			1							1	180		180
BOEING (rSOC Demonstrator)	United States	2015	2017	SOEC	1									0.15	37.5		37.5
SoCalGas	United States	2015		PEM		1								0.07			13.96
Energy & Smartgrid Corsica	France	2016		ALK	1										10		10
ElectroHgena	France	2016	2019	PEM						1	1	1					
Hassfurt	Germany	2016		PEM	1	1			1					1.25			260.42
HPEM2GAS (R&D)	Germany	2016	2019	PEM		1								0.18			37.5
smart grid solar - arzberg	Germany	2016		PEM	1		1							0.08			15.63
HELMETH	Germany	2016	2017	SOEC							1	1		0.015	5.4		5.4
Power to flex	Germany	2016	2019	Unknown PtX	1		1		1								

Tomakomai	Japan	2016	2019	Fossil				1								100000	14108.92
Shoro Dam in Shiranuka-cho, Shiranuka-gun, Hokkaido	Japan	2016		ALK	1										35		35
NEDO kofu city, Yamanashi Prefecture	Japan	2016	2020	Unknown PtX	1												
Emirate Steel Indusrty	United Arab Emirates	2016		Fossil				1								800000	112871.34
Fife, Levenmouth Community Energy Project	United Kingdom	2016		ALK	1		1							0.37			78.87
Naval Facilities Engineering Command, Engineering and Expeditionary Warfare Center	United States	2016		SOEC	1									0.05			13.89
H2FUTURE	Austria	2017	2021	PEM				1						6			1250
DEMO4GRID	Austria	2017	2022	ALK			1		1					4			952.38
Enbridge P2G toronto	Canada	2017	2017	PEM		1								2			416.67
Cerro Pabellón Microgrid 450 kWh Hydrogen ESS - Enel S.p.A	Chile	2017		Unknown PtX	1												
Guangdong Synergy Hydrogen Power Technology Co.	China	2017		PEM			1							3			625
Foshan hydrogen city first part	China	2017		PEM			1							3			625
Hebei- China	China	2017		ALK	1									4	400		400
CPI Zaoquan thermal power plant in China's Ningxia region	China	2017		ALK				1						0.10	20		20
Haldor Topsoe - El-Opgraderet Biogas II	Denmark	2017	2020	SOEC							1			0.04	10		10

FaHyence	France	2017		ALK			1								30		30
Minatec's semiconductor labs in Grenoble	France	2017		ALK				1							30		30
H&R Ölwerke Hamburg-Neuhof	Germany	2017		PEM				1						5			1041.67
Wyhlen hydroelectric power plant, ENERGIEDIENST, ENBW Group, Center For Solar Energy	Germany	2017		ALK	1										200		200
Alzey, Exytron Null-E	Germany	2017		ALK	1				1					0.063	10		10
Energy in the Container, Fraunhofer IISB, Erlangen, Leistungszentren Elektroniksysteme (LZE)	Germany	2017		PEM	1												
Musashi-Mizonokuchi Station	Japan	2017		PEM	1										1		1
Energy observer	Japan	2017		Unknown PtX	1		1										
ASKO Midt-Norge	Norway	2017		ALK			1								150		150
Tauron CO2-SNG	Poland	2017		Unknown PtX						1	1	1					
Lam Takhong Wind Hydrogen Hybrid Project- EGAT	Thailand	2017		PEM	1									1.2			250
Surf'n'Turf Orkney	United Kingdom	2017		PEM	1									0.5			104.17
Zero Impact Production (ZIP) Hydrogen facility, phase 1	United States	2017		PEM			1							2.5	450		450
Kidman Park in Adelaide depot	Australia	2018		Unknown PtX		1											
Moreland garbage truck filling station	Australia	2018					1										
RAG	Austria	2018		PEM							1			0.5	100		100

[redacted]																	
Foshan hydrogen city 2	China	2018		PEM			1							10			2083.3
Tongji solar hybrid hydrogen refueling station	China	2018		Unknown PtX			1										
HyBALANCE	Denmark	2018	2020	PEM			1	1						1.2	230		230
Demonstration of bio-CO2 products, Bio economy+	Finland	2018	2018	PEM						1			1	0.03	4		4
GRHYD (inj in NG grid)	France	2018	2022	PEM		1									10		10
GRHYD (Hythane)	France	2018	2022	Unknown PtX								1					
Wind to gas Brunsbüttel	Germany	2018		PEM		1								2.4	500		500
GrInHy	Germany	2018	209	SOEC	1									0.15	37.5		37.5
REFLEX	Italy	2018	2020	SOEC	1									0.08	16		16
STORE And GO, Troia Italy	Italy	2018	2021	Unknown PtX							1	1					
Tomamae Town, Hokkaido	Japan	2018		PEM	1									0.14			28.13
Yokohama City Wind Power Plant (Hama Wing)	Japan	2018		PEM			1								10		10
Sendai City	Japan	2018		PEM	1									0.024			5
Rakuten Seimei Park Miyagi	Japan	2018		PEM	1										1		1
Tokyu Construction Institute of Technology	Japan	2018		PEM	1										1		1

Power plant in Lebanon for a Power Plant Cooling application	Lebanon	2018		ALK				1						0.11	20		20
Delfzijl - Hystock	Netherlands	2018		PEM				1			1	1		1.2			250
Natuurgasbuffer Zuidwending	Netherlands	2018		PEM			1							1			208.33
Semakau island microgrid Engie (SPORE)	Singapore	2018		Unknown PtX	1		1										
CoSin: Synthetic Natural Gas from Sewage, Barcelona	Spain	2018	2019	ALK							1			0.04			8.81
Oxelösund Forklifts	Sweden	2018		PEM			1										
SunLine Transit Agency, Palm Springs	United States	2018		PEM			1								417		417
Hydrogen Park SA, Tonsley Park project	Australia	2019		PEM		1								1.25			260.47
ATCO microgrid	Australia	2019		PEM		1								0.3			62.5
Toyota Australia, Altona, Victoria	Australia	2019		PEM			1							0.25			52.08
VOESTALPINE LINZ	Austria	2019		PEM				1						6			1250
North West Sturgeon refinery	Canada	2019		Fossil				1								1200000	169307.0
Nutrien (former Agrium) fertilizer	Canada	2019		Fossil						1						300000	42326.75
Guangdong Synergy Hydrogen Power Technology Co.	China	2019		PEM			1							10			2083.33
NT Bene, Parnu	Estonia	2019		PEM			1								185		185

Balance	EU	2019	2019	SOEC	1									0.01	2		2
VTT	Finland	2019		PEM	1									0.02	4.1		4.10
Jupiter 1000	France	2019	2021	ALK		1					1			1	200		200
GNVert H2 filling station with Engie	France	2019		PEM			1								37		37
SPHYNX, R&D	France	2019		Unknown PtX	1	1		1	1								
eFarm	Germany	2019		PEM			1							1.13			234.38
Maximator	Germany	2019		PEM			1							0.83			173.61
Rostock, Exytron Demonstrationsanlage	Germany	2019		ALK	1				1					0.02	4		4
Sarawak Energy - Shell Malaysia (Borneo)	Malaysia	2019		Unknown PtX			1							0.05			11.11
Duwaal	Netherlands	2019		PEM			1							2			416.67
HAEOLUS	Norway	2019	2021	PEM	1		1	1						2			416.67
H2 Energy	Switzerland	2019		PEM			1							2			416.67
Solothurn, STORE&GO	Switzerland	2019		PEM							1			0.7			145.83
Hydrogen plant - Orkney Islands, Scotland (Building Innovative Green Hydrogen BIG HIT)	United Kingdom	2019		PEM			1							1			208.33
HyDeploy	United Kingdom	2019		PEM		1								0.5			104.17

ACT project	Australia	2020		PEM			1							1.25			260.42
Jemena Gas Network - H2GO project	Australia	2020		Unknown PtX		1											
Air Liquide Becancour	Canada	2020		PEM			1	1						20			4166.67
Sinopec Eastern China CCS	China	2020		Fossil				1								500000	62689.30
Yanchang Integrated Carbon Capture and Storage Demonstration	China	2020		Fossil						1						410000	24537.0
Fredericia, Denmark, Shell refinery	Denmark	2020		ALK				1						20			4761.904762
METHYCENTRE	France	2020	2026	PEM			1				1	1		0.25			52.08
Port-Jérôme	France	2020		Unknown PtX				1				1					
Hygreen	France	2020	2027	Unknown PtX	1	1	1										
REFHYNE	Germany	2020	2022	PEM				1						10			2083.33
Wind to Gas Südermarsch	Germany	2020		Unknown PtX		1								2.4			533.33
Salzgitter Clean Hydrogen project	Germany	2020		PEM				1						20	400		400
Carbazol pilot plant, University of Erlangen-Nürnberg	Germany	2020		Unknown PtX						1							
FH2R Toshiba Tohoku Iwatani	Japan	2020		Unknown PtX			1							10			2222.22
Fukushima Power-to-gas Hydrogen Project	Japan	2020	2021	ALK	1		1	1						10			2380.95

Nordic Blue Crude	Norway	2020		SOEC									1	20			5555.56
Green hydrogen Project, Mohammad Bin Rashid Solar Park	United Arab Emirates	2020		Unknown PtX													
NEL - Nikola	United States	2020		Unknown PtX			1							1000			222222.22
Nikola	United States	2020		ALK			1								463		463
Engie - Yara Pilbara test	Australia	2021		PEM						1				55			11458.33
Port Lincoln project, Eyre Peninsula	Australia	2021		PEM	1					1				15			3125
Element One	Germany	2022		Unknown PtX		1		1						100			22222.22
Rotterdam BP refinery	Netherlands	2022		Unknown PtX				1						250			55555.56
Wind meets gas	Netherlands	2022		Unknown PtX				1						100			22222.22
ECB Paraguay biofuel project	Paraguay	2022		Unknown PtX									1	310			68888.89
Lake Charles Methanol	United States	2022		Fossil						1						4200000	251354.60
SkyNRG	Netherlands	2022		Unknown PtX									1				
Hybridge	Germany	2023		Unknown PtX			1	1			1			100			22222.22
Magnum, Eemshaven	Netherlands	2023		Fossil	1											1300000	183415.93
Ijmuiden	Netherlands	2023		Unknown PtX				1						100			22222.22
Teesside collective	United Kingdom	2024		Fossil				1								680000	85257.44

Acorn Aberdeenshire	United Kingdom	2024		Fossil				1								500000	70544.59
South West Hub	Australia	2025		Fossil				1								2500000	313446.48
H2V PRODUCT	France	2025		ALK		1		1						700			166666.67
H-Vision	Netherlands	2025		Fossil				1								2000000	282178.35
H21 North of England	United Kingdom	2028		Fossil		1										1.6E+07	2275062.94

Figure 7-1 presents a list of pilot projects announced by utilities in the United States.

US hydrogen pilot projects announced by natural gas utility operators

Power generation, Transportation, Hydrogen production, Hydrogen storage, Pipeline transmission and distribution, Appliance end use

Company	Description	Location	Announced	Partners
CenterPoint Energy Inc.	Produce green hydrogen, blend less than 5% into low-pressure portions of CenterPoint's Minnesota distribution system.	Minneapolis	08/06/20	None
Chesapeake Utilities Corp.	Use 4% blend of hydrogen to fuel gas turbine at Eight Flags Energy combined heat and power plant.	Amelia Island, Fla.	02/25/21	Solar Turbines Inc.
Dominion Energy	Four-phase pilot project aiming for 5% hydrogen blending capability in Utah distribution system by 2030.	Salt Lake City	Q3'20	None
Dominion Energy	Test 5% blend of hydrogen in training facility system before blending hydrogen into distribution system.	North Carolina	04/19/21	North Carolina Utilities Commission
Duke Energy Corp.	Study hydrogen production, storage; produce green hydrogen to power gas turbine at Clemson University's cogeneration plant.	Clemson, S.C.	12/10/20	Siemens Energy AG, Clemson University
National Grid PLC	Pilot the Energy Transfer System: a combined hydrogen production, storage and distribution facility.	Capital Region of New York	03/11/21	Standard Hydrogen Corp.
New Jersey Resources Corp.	Produce hydrogen from solar power, blend supplies into gas distribution system.	Howell, N.J.	11/30/20	None
Northwest Natural Holding Co.	Use local renewable power to produce hydrogen for use in Oregon distribution system.	Eugene, Ore.	10/08/20	Eugene Water & Electric Board, Bonneville Environmental Foundation
Puget Sound Energy Inc.	Blend hydrogen into natural gas training facility system; test for leaks, air and gas quality, impact on end-use appliances.	Seattle	April 2021	Western Energy Institute, American Gas Association
San Diego Gas & Electric Co.	Produce green hydrogen on-site at microgrid, inject supplies into storage containers for use in fuel cells to produce electricity.	Borrego Springs, Calif.	04/19/21	None
San Diego Gas & Electric Co.	Produce green hydrogen on-site at Palomar Energy Center to power fuel cell vehicles, blend hydrogen into plant's gas stream, cool turbines.	Escondido, Calif.	04/19/21	None
South Jersey Industries Inc.	Produce hydrogen using electric power from offshore wind, study blending in gas grid.	New Jersey	12/15/20	Atlantic Shores Offshore Wind LLC
Southern California Gas Co., San Diego Gas & Electric	Blend hydrogen into isolated sections of gas pipeline at 1% to 20% concentrations.	California	11/23/20	None
Southern California Gas Co.	Develop prototype fuel cell design to power heavy-duty trucks, transit buses.	California	08/26/20	Cummins Inc., U.S. Energy Department

(a)

US hydrogen pilot projects announced by natural gas utility operators

Power generation, Transportation, Hydrogen production, Hydrogen storage, Pipeline transmission and distribution, Appliance end use

Company	Description	Location	Announced	Partners
Southern California Gas Co.	Modify commercial marine vessel to run on hydrogen fuel cells.	Port of Long Beach, Calif.; Port of San Francisco, Calif.	04/27/21	Zero Emission Industries, California Energy Commission
Southern California Gas Co.	Demonstration test a modular 200-kW electrolyzer that can be stacked for use in microgrid.	California	04/20/21	H2U Technologies Inc.
Southern California Gas Co.	Produce hydrogen on-site to power hydrogen fuel cell buses using renewable natural gas as feedstock.	Thousand Palms, Calif.	04/21/21	SunLine Transit Agency
Southern California Gas Co.	Demonstrate hydrogen-natural gas blend's potential to power systems, appliances in model home.	Downey, Calif.	12/15/20	ATCO Ltd.
Southern California Gas Co.	Field-test technology that separates, compresses hydrogen from natural gas blends.	Pico Rivera, Calif.	12/16/20	HyET Hydrogen
Southern California Gas Co.	Produce green hydrogen using solar, wind power to create zero-emissions energy system on college campus.	Irvine, Calif.	07/26/21	University of California, Irvine
Southern California Gas Co.	Demonstrate, commercialize technology using solar power to separate hydrogen from natural gas, capture CO2 in solid form.	Los Angeles	07/26/21	University of California, Los Angeles
Southern Co. Gas, National Grid PLC, One Gas Inc., New Jersey Natural Gas Co.	Evaluate impact of hydrogen blends in gas pipelines; study life-cycle emissions from blending; quantify costs and opportunities.	National Renewable Energy Laboratory, Sandia National Laboratories, Pacific Northwest National Laboratory, Argonne National Laboratory	11/18/20	U.S. Energy Department and about 20 industry, academia and public partners
Southern Co. Gas	Advance microbial electrolysis system technology to produce hydrogen from food waste; test end uses.	East Tennessee	08/03/21	Electro-Active Technologies, T2M Global
Southwest Gas Holdings Co.	Inject hydrogen into gas grid at training facility to assess optimal blend percentages, safety, economics, performance.	Tempe, Ariz.	05/07/21	Arizona State University
Southwest Gas Holdings Co.	Inject hydrogen into gas grid at training facility to assess optimal blend percentages, safety, economics, performance.	Henderson, Nev.	08/06/21	University of Nevada, Las Vegas
Texas Gas Service Co. Inc., Southern California Gas Co.	Produce hydrogen from electrolysis and renewable natural gas to power computing center fuel cell, supply fuel cell electric vehicle filling station.	Austin, Texas	09/15/20	Frontier Energy Inc., Gas Technology Institute, U.S. Department of Energy, University of Texas at Austin

As of Sept. 20, 2021.
Source: S&P Global Market Intelligence

(b)

Figure 7-1 List of pilot projects announced by the natural gas utility operators in USA

[redacted]

[redacted]

[redacted]

Conclusion

The world will need to adopt new energy sources to meet the net-zero by 2050 goal from the Paris agreement. The Government of Canada along with some of its provincial, regional and municipal counterparts have published various policies to address numerous environmental challenges such as global warming, air pollution and climate change and will require a significant reduction and management of greenhouse gas emissions. [redacted]

Table 11 presents a summary of the potential hydrogen effect on materials in a natural gas system, and Table 12 shows the issues that may arise due to presence of hydrogen. The current state of assets needs to be evaluated to ensure a safe hydrogen injection limit; hence, every gas distribution network currently demands a case-by-case assessment before injecting hydrogen-blended natural gas. It is important to note that apart from the technological challenges, there are also regulatory and financial barriers to be overcome.

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