UNIVERSITY
OF TURKU

Welding of hydrogen pipelines

Unique challenges posed by hydrogen in fabrication and repair of transmission pipelines

Mechanical Engineering/Department of Mechanical and Materials Engineering

Bachelor's thesis

Author:
Aarni Järvinen

13.5.2026
Turku

Bachelor's thesis

Subject: Mechanical Engineering

Author(s): Aarni Järvinen

Title: Welding of hydrogen pipelines

Supervisor(s): Assistant Professor Mohsen Amraei

Number of pages: 33 pages

Date: 13.5.2026

Hydrogen as an energy carrier and its transportation are currently major research topics in the energy sector, both globally and within Europe. Finland aims to become a forerunner in the European hydrogen economy, which necessitates a reliable and safe cross-border distribution infrastructure. However, hydrogen-induced changes in the mechanical properties of pipeline materials, particularly embrittlement, pose significant challenges in developing durable solutions.

The objective of this thesis is to examine the most common material and transportation challenges associated with the transmission of pressurized hydrogen, both in converted natural gas pipelines and in potential new-build gas networks. The specific challenges posed by hydrogen regarding the service life and operational reliability of pipelines are analyzed in greater detail from the perspective of the welding operations required for assembly and repair. Furthermore, the study reviews scientific articles, international standards, and technical recommendations concerning the welding of hydrogen gas pipelines, while identifying potential safety risks.

Vetykaasun kantama energia ja sen kuljetus ovat tällä hetkellä merkittäviä tutkimusaiheita energia-alalla niin globaalisti, kuin Euroopassa. Suomen tavoite on nousta Euroopan vetytalouden edelläkävijäksi, mikä vaatii luotettavaa ja turvallista rajojen yli ylettyvää jakeluinfrastruktuuria. Vedyn aiheuttamat muutokset putkistomateriaalien mekaanisissa ominaisuuksissa, varsinkin haurastuminen, aiheuttavat haasteita kestävien ratkaisujen valmistamisessa.

Tämän tutkielman tavoitteena on käydä läpi yleisimpiä materiaali- ja kuljetushaasteita paineistetun vedyn siirtämisessä niin konvertoiduissa maakaasuputkissa kuin potentiaalisissa uudisrakennetuissa kaasuputkistoissa. Vedyn asettamia erikoishaasteita putkistojen käyttöiän ja toimintavarmuuden kannalta tarkastellaan tutkielmassa tarkemmin kokoonpano- ja korjaustoimien vaatimien hitsaustoimien näkökulmasta. Tekstissä käydään läpi tieteellisiä artikkeleita, kansainvälisiä standardeja ja teknisiä suosituksia vetykaasuputkien hitsaustoimissa, sekä havainnoidaan potentiaalisia vedyn tuottamia turvallisuusriskejä.

Keywords: Hydrogen embrittlement, hydrogen induced cracking, diffusion, solubility, microstructure, heat-affected-zone, in-service welding, internal stress

Table of contents

1 Introduction

As the global energy sector finds itself in a transitional phase towards decarbonization, secure, consistent and low emission energy supplies are required. Hydrogen has the potential to become a staple part of the European energy mix, fuelling energy-intensive sectors such as transportation and industry, while also transporting and storing energy. Hydrogen also has the advantage of being able to be produced from varying renewable sources across the world. It has also been used as an agent in creating other synthetic fuels, increasing its usability in our modern energy infrastructure.

Currently several countries have their sights on creating a stable and low-emission hydrogen economy. Notably the European Union and Finland have a goal of achieving a net-zero emission energy economy in near decades. To achieve these goals, an effective and secure infrastructure for hydrogen transport is required. On estimate, most of the current hydrogen usage is in the central parts of Europe, requiring solutions that can connect producers with users.

The main challenges compared to hydrogen reside in its interaction with pipeline materials, such as low-alloy steel. Hydrogen has the tendency to absorb into low-alloy steels, causing material degradation and weakening its mechanical properties such as ductility and fracture toughness.

These interactions must be mitigated to produce safe and reliable transportation infrastructure, however the welding processes commonly used in pipeline production have been noted to increase the hydrogen uptake in pipe materials as heat and alterations in microstructure caused by welding have a positive factor for hydrogen diffusion and therefore increasing the risk of material failure.

This thesis focuses more prominently on the processes and material selections for hydrogen transmission pipelines, identifying practises to mitigate hydrogen interaction during and after welding processes to ensure a higher level on service life and operation. Finding answers for the following questions:

1. How hydrogen affects pipeline metals?
2. How to mitigate hydrogen uptake during welding processes?
3. Risks associated with welding in hydrogen rich environments.

This thesis aims to provide an overview of the current status of hydrogen infrastructure in Finland and its prospects while considering the current industry standards regarding welding of hydrogen pipelines.

2 Hydrogen economy and its significance as an energy source

2.1 Hydrogen economy and EU

2.1.1 Energy security

Renewable Hydrogen development for energy infrastructure is a priority for the European Union due to changes in the climate and political situations in the last decades. The Union's goal of a climate-neutral economy requires new and effective forms of energy transfer and storage to match the large needs of energy intensive sectors like transportation, industrial processes and heating. A historical dependency on Russian imports of fossil fuels for the energy sector has caused hardships for the economies of European countries due to the disruptions in the global energy market created by recent political events. [1], [2]

The European commission has set targets to ensure future risks for energy shortages are mitigated, and the movement towards clean energy keeps going forward. Due to the nature of green energy generation and its large dependency on the time of day and weather, large storage capacity for energy is needed. This can be met with hydrogen-based applications such as batteries, pumped-storage hydropower, or using hydrogen as a gaseous energy carrier. [1]

High price changes and the usage of energy demand as a weapon are meant to be made unfeasible for Russia against the EU. The diversifying of energy sources also supports the EU to react more efficiently to global climate changes that can make sourcing energy from certain sources more difficult. [3]

According to the EU, renewable Hydrogen will play a key role in decarbonizing certain economic sectors more efficiently than other clean energy sources. Hydrogen can also be used as a component for producing new industrial products such as fertilizers in the agricultural sector, as an agent in steel manufacturing, and for creating other fuels such as methanol, kerosine, or diesel. Therefore, already existing raw-material and fuel infrastructure can be reused on differing levels with hydrogen. [3]

Due to the new conversion processes, changing the form of energy is not considered efficient with modern technology and resources. Therefore, green hydrogen and other similar fuels are not competitive yet with other energy manufacturing processes. The heat and oxygen produced by these processes can be utilized to improve the efficiency of hydrogen production in the long term. [4]

2.1.2 Policy

As an answer to the need of more green energy and due to the uncertainties of modern global energy market, the European Union has implemented its plan for the production and usage of renewable energy with REPowerEU. The plan contains an aim for producing up to 10 million tonnes as well as importing an equal amount of hydrogen by 2030. [1]

Renewable hydrogen is also planned to cover about 10% of the EU’s energy needs by 2050. The Union has also revised its Renewable energy Directive in 2023, setting an overall binding target of at least 42.5% renewable energy in EU’s energy mix by 2030. [2]

The directive also includes the Hydrogen and decarbonised gas market package, that is meant to introduce a regulatory framework for dedicated hydrogen infrastructure. The package contains rules for the hydrogen market and infrastructure, as well as remove barriers that disrupt their development. It also focuses on creating right conditions for the repurpose of existing natural gas infrastructure for hydrogen. [3]

2.1.3 Ventures

The Union has many ongoing projects to improve and increase the use of hydrogen as an energy source. The Clean Hydrogen Joint Undertaking is a public private partnership supporting research and innovation focusing on hydrogen technologies. The partnership engages in pre-normative research and technical cooperation and policy engagement to create groundwork for international standards and regulations for cleaner integration and rollout of new energy systems. [5]

2.2 Hydrogen in Finland

2.2.1 Economic needs and possibilities

Hydrogen economy has notable potential in several Finnish economy sectors, such as energy, industry and transportation. As requirements for more green energy sources has increased, one of Finland's greatest strengths is the decarbonization of its electric power generation. It is also backed up by a stable national energy grid and potential for the increase of future low-carbon energy generation with additional construction projects. [6]

In 2020 Finland produced on estimate 145 000 tons of hydrogen for industrial needs. This amounted to 1.5% of all hydrogen produced in the EU. In addition to this, hydrogen is produced by other industrial processes as a byproduct. This is notably lower, on estimate as 23 000 tons a year in 2020. Main usage for hydrogen in Finland is in oil refinement, biofuel production, as well as mining and chemical industry. [6]

However, there are also some difficulties and limitations when it comes to the development of hydrogen economy in the region. Finland's geographical location places it further away from the potential main market of hydrogen consumption.[6] The European Hydrogen Observatory reports that in 2023 Europe’s top 5 hydrogen importers were mainly located in the central European industrial region (with the Netherlands importing up to 66% of all hydrogen traded inside Europe). [7]

This would potentially call for infrastructure that focuses on the transportation of hydrogen to areas with higher demands for ensuring viable hydrogen production. However, Finland is not alone with this as the same geographical situations applies to the other Nordic countries. This potential has been recognized in the Nordics and plans are being made for future projects concerning new gas transmission lines connecting Finland with other countries across the Baltic sea. [6]

2.2.2 Projects

The Finnish government has adopted a resolution in 2023 containing a goal to become the European leader in the hydrogen economy. This includes the goal to produce on estimate 10% of EU’s emission free hydrogen. [8]

Finland has several ongoing projects concerning the hydrogen economy and the increase of hydrogen in the value chain (Fig. 1). The Nordic Hydrogen Route Project between the Finnish natural gas transmission operator and the Swedish energy infrastructure company Nordion Energi is meant to accelerate the creation and growth of hydrogen economy via a cross-border hydrogen infrastructure. The network of pipelines will make the hydrogen produced in the northern Europe more accessible to consumers around the Bothnian Bay and industrial centres in Sweden. [9]

In addition, Gasgrid also has a part in plans for other hydrogen projects across the Baltic Sea, such as Nordic-Baltic Hydrogen corridor that focuses on crating hydrogen transmission lines through the Baltic coast from Estonia to Germany [10]. Gasgrid is also a part of Baltic Sea Hydrogen Collector project. Its focus is on studying a possibility of hydrogen transmission lines across the sea with the mainline connecting Finland with Germany and Other branches connecting Sweden and Åland. These projects are meant to increase and develop green hydrogen production in Northern Europe and will also aid in the storage of energy for the future. [11]

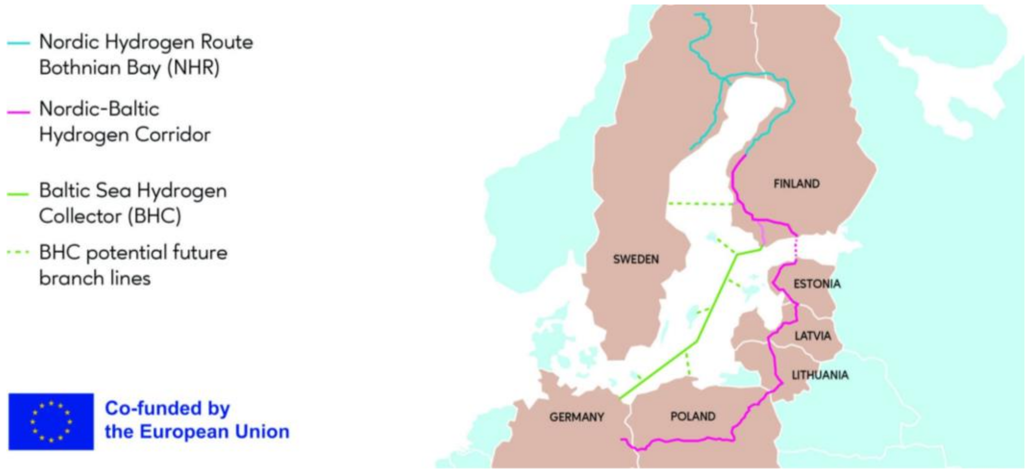

Figure 1: Planned potential hydrogen infrastructure projects [10].

3 Hydrogen transmission

3.1 Properties of hydrogen

3.1.1 Energy density

Hydrogen's properties are unique for several factors. Despite being thought as the simplest element with the atomic number of 1 and consisting of only 1 proton and electron, it's the most common element on the surface of earth and can be found from various sources. Most know sources being water and biomass, as well as fossil fuel. Having the lightest weight of its molecule, hydrogen also has the fastest diffusion rate and therefore with weak intermolecular forces it can permeate and adhere to materials quickly. This phenomenon and the reversibility of the process pose risks as well as possibilities for hydrogen storage and transmission. This topic will be focused more on in chapter 3.1.2. Hydrogen has a diverse chemistry due to its ability to replace its strong H_2 molecule bond with similarly strong bonds with other elements. It can also create strong bonds with most of other elements, and it can be found in variable chemical compounds. [12]

Hydrogen has a potential to be a very potent energy source. It has the highest energy per mass of any fossil or hydrocarbon fuel, known as the gravimetric density at around 120 MJ/kg (Fig.2). For reference, gasoline is around 46 MJ/kg [13]. Despite having a high amount for energy per mass, it is also important to take into consideration the matters volumetric properties. This is what modern hydrogen energy solutions must combat with due to hydrogens noticeably low volumetric energy density of around 10.1 MJ/L in liquid state, whereas gasoline has a density of 34.2 MJ/L. The volumetric density can be improved with pressurization in a gas state, however, the density is still relatively low with around 5.6MJ/L with a pressurization of 700 bars. Hydrogen can also be liquified by bringing its temperature down to about –253°C in atmospheric pressure. [13]

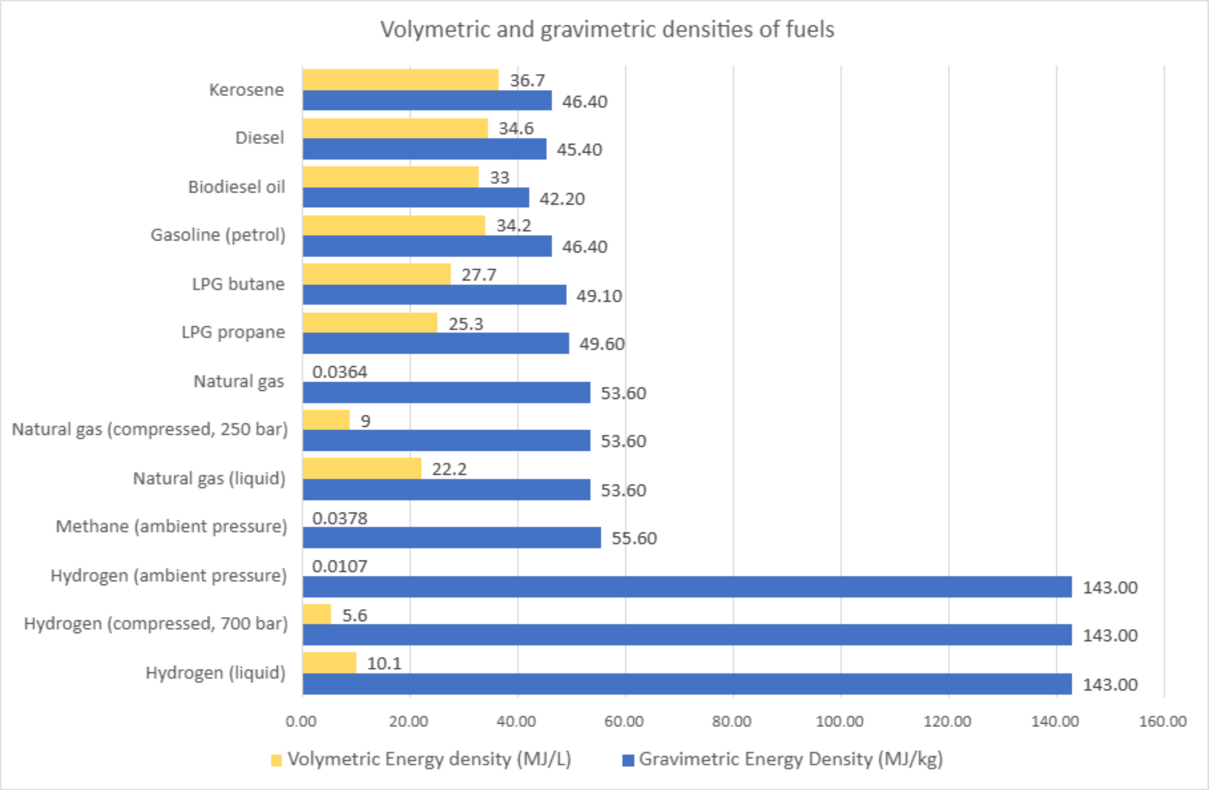

Figure 2: The gravimetric and volumetric energy densities of various fuels. Based on the tables of Hossain et al. [13].

Due to the difficulty of increasing hydrogens volumetric energy density, there are distinct logistical issues related to it. Cooled-down hydrogen requires temperature-controlled systems with insulative materials, while pressurization requires strong and safe systems able to work reliably. [13]

In this literature review, the focus will be mainly on the hydrogen’s effects on the pipeline and weld materials in a gas phase.

3.1.2 Solubility and diffusivity with pipe materials

Due to the nature of hydrogens solubility and diffusivity, it produces a problem when presented to other surface materials in storage and especially in transit [13]. For our case we will mainly be focusing on the effects hydrogen has on pipeline and weld materials in a gas phase.

When the gaseous hydrogen molecules encounter pipe materials, usually low alloy steels, they become adhered to the surface with weak Wan der Waals forces. This is called physisorption. After adhering to the surface the hydrogen molecules, after receiving energy dissociate into individual atoms that will in turn form chemical bonds with metal atoms on the surface known as chemisorption. Heat sources such as welding processes can cause an increase in hydrogen diffusion and is therefore one of the main risks in pipeline hydrogen embrittlement. [14]

Due to outside pressure or large concentration, the atoms on the surface begin to be absorbed into the metal. The atoms follow a common path of locating to sites of structural imperfections or lattice defect sites. These can be for example vacancies, grain boundaries or dislocations in the materials structure. This is visualized in fig.3. The locations are called hydrogen traps and cause the accumulation of hydrogen in the material. This accumulation happens mostly in areas of high stress concentrations or tips of already formed cracks in the steel. [14]

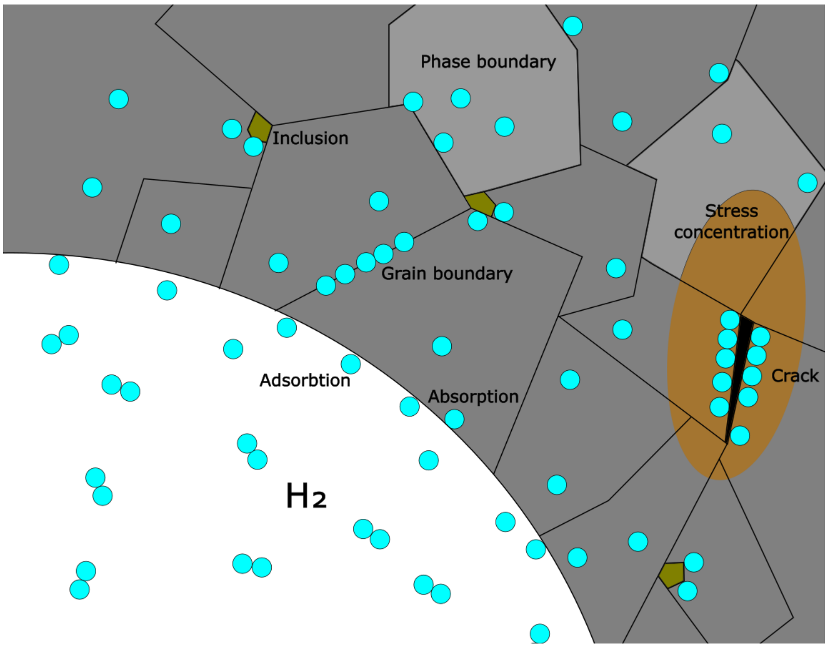

Figure 3: Hydrogen diffusion in a pipe steel. Based on the graphic of Zhang et al. [15].

The thermal cycles present in welding of gas pipelines create non-equilibrium phase transformations. These metallurgical changes affect the microstructure, stress-state and mechanical properties of the pipe material, potentially making it more susceptible to hydrogen diffusion and accumulation. [14]

Ferritic steels have a significantly higher diffusion rate when compared to austenite steels. This is caused by the more open crystal lattice structure that can have a diffusion rate almost 1000 times faster than austenitic alloys. In contrast, austenitic steels have a higher solubility with low diffusivity (fig.4). Therefore, steels that are austenitic at or near room temperatures can resist hydrogen induced failure mechanisms more efficiently due to the slowness of hydrogens movement in the material at room temperature. [16]

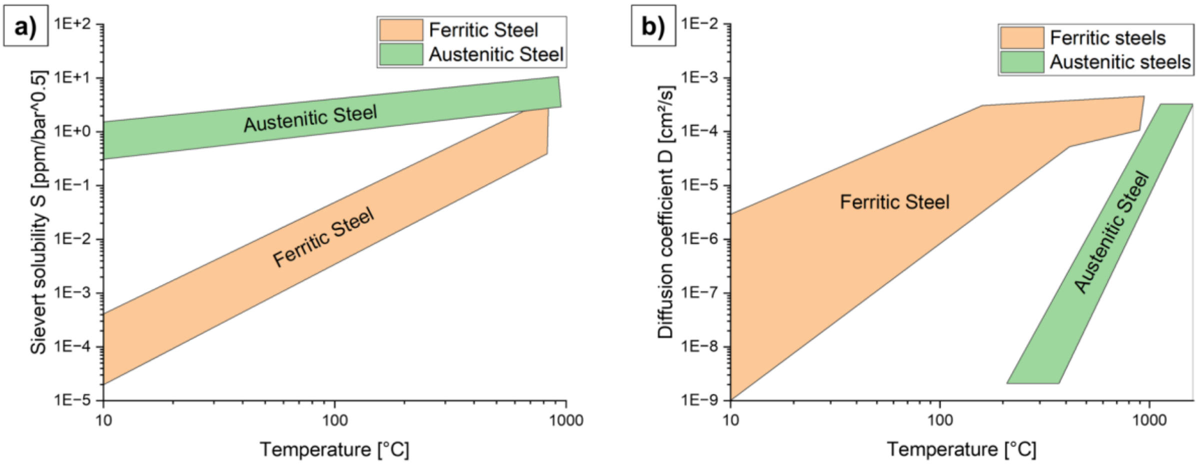

Figure 4: Comparison of Sievert’s solubility constant (a) and diffusion coefficient (b) in dependence of ferritic and austenitic steels [16].

Since steels microstructure can change widely due to the heat received and lost during welding processes wide range of structures can form in the material. Harder and more brittle microstructures such as martensite or bainite are most at risk of hydrogen induced failure due to their low capacity of plastic deformation and high internal stresses. [17]

3.1.3 Hydrogen embrittlement and Hydrogen induced cracking

Once the hydrogen has accumulated in the material it begins to affect the metals structural properties. The Hydrogen embrittlement has several failure mechanisms that are thought to act synergistically in the structure. The trapped hydrogen can form into molecules causing internal pressure in the structure causing plastic and elastic changes in the microstructure. The hydrogen enhanced local plasticity lowers the needed energy demand for moving dislocations in the structure creating zones with highly localized deformation enhancing crack formation. [14]

Hydrogen induced cracking is caused by the blistering and tearing of the material due to the rising internal pressures caused by hydrogen. This also enhances the accumulation of hydrogen to stress sites and in turn has a higher risk of Hydrogen enhanced decohesion. This mechanism weakens the interatomic forces for cohesion of the lattice, causing brittle fractures. The current theory dictates that several Hydrogen embrittlement failure mechanisms can work simultaneously in the materials. [14]

Due to pressure fluctuations in transmission pipelines caused by changing demands or pressure station turning off the pipelines experience cyclic loading due from the hoop stress caused by the pressure. This loading creates a risk of increasing fatigue crack growth in an already embrittled steel creating higher risks for material failures. [18]

The degradation of mechanical properties can be divided into surface and internal hydrogen embrittlement, with the former being called Hydrogen environment Embrittlement. Internal hydrogen embrittlement is caused by hydrogen trapped in the material during manufacturing. [14]

3.2 Production and transmission

3.2.1 Production of Hydrogen

Hydrogen can be produced by a variety of processes and sources. The energy industry has taken to use a colour spectrum to differentiate how specific hydrogen products were produced. We will focus on the divide between blue and green hydrogen. Blue hydrogen is produced from fossil fuels by hydrocarbon reforming and hydrocarbon Pyrolysis. Reforming methods include steam reforming and partial oxidization as well as autothermal reforming. [19]

Green hydrogen is produced from renewable sources and can be divided into biomass processes and water splitting. Biomass processes can also be divided into Biological (bio-photolysis, dark fermentation and photo fermentation) and thermochemical processes (pyrolysis, gasification, combustion and liquefication). [19]

Currently fossil fuel-based hydrogen products are the most used due to their relatively low cost to high efficiency compared to other processes. Water electrolysis has the potential to rise as a viable renewable source for hydrogen. But is of yet not competitive with fossil-based processes. [19]

3.2.2 Pressure and velocity

The pressurization and transmission velocity of hydrogen pipelines varies greatly between countries and the intended use of the pipelines. The original transmitted gas and its contents in pipelines also affect regulations for allowable hydrogen transmission. [18]

Due to the significantly lower volumetric energy density of hydrogen mentioned before, when compared to the energy transmission of natural gas at the equal amount of volume transmitted, only a third of the energy is delivered. To match the previous supply of energy, hydrogen transmission would require three times increase in volumetric flow rate. Such capacity increased in already existing pipelines would increase the risks of flow characteristics that are above the safety limits set by the industry and standards. These flow characteristics, such as increased velocity can degrade the interior of the pipes via eroding the surfaces, known as erosional velocity. Compressibility and pressure drop experienced in the pipe can also have unexpected effects for the integrity of the pipelines as well as the control of the gas flow [18]. Increased velocity in transmission can also affect the in-service welding of pipelines due to the increased pressure and convection of heat via hydrogen gas. This will be focused more on in chapter 4.

Several existing pipelines dedicated for hydrogen transmission pipelines have operated up to 100 bar pressure. However, high pressure has been noted to increase the solubility of hydrogen into pipeline steels and therefore should be avoided for general use. According to a Linear Elastic Fracture Analysis performed by Lipiäinen et al. (2023) potential re-use of existing NG pipelines for hydrogen will require pressure reduction to prevent significant material degradation and fatigue crack growth. They suggest that an 80 bar transmission pipeline could therefore be repurposed to the transmission of hydrogen with up to 10% mixture with 65 to 75 bar and 100% hydrogen with 45-55 bar. [18]

Such cases have already been put to test, for example, Netherlands energy network operator Gasunie converted an existing natural gas pipeline with design pressure of 66.2 bar to service with an 80% hydrogen blend with a pressurization of 35 bar. [20]

3.3 Compatibility with NG pipelines

Repurposing existing natural gas pipelines poses a possibility of significant economic savings, as some estimates evaluate that repurposing existing pipelines for hydrogen can cost around 0.2-0.6 M€/km, whereas constructing new hydrogen pipelines is estimated at 1.4-3.4 M€/km. [18]

Around 60% of European pipelines are estimated to be steel types of API 5L Gr. B, X42, X52 and X60. They are generally considered suitable for the carrying of hydrogen gas. Most other steel grades used are of higher hardness of steel and therefore pose a higher risk of hydrogen embrittlement. [18]

Measures to combat the embrittlement caused by hydrogen are researched constantly. The use of inhibitors like O_2 and CO can help mitigate hydrogen diffusivity. Modifications can also potentially be made to existing pipelines to improve them such as pipe-in-pipe structures or inner coatings to protect the steel. These are however currently considered costly and inefficient solutions due to their complexity. [18]

Finland's transmission network consists of 1150 km of high-pressure carbon steel pipelines and in addition 60 km of pipelines with lower pressurization. According to approximations around 85% of the pipelines operate with 54bar pressurization and less than tenth of the pipelines has the possibility to use up to 80% pressure. The nominal diameter (DN) of the pipe ranges between DN100 and DN1000. Low pressure polyethylene pipelines have a unified length of around 1997 km. Finland also has an offshore pipeline connecting it to Estonia with a length of 77 km and diameter of DN500 designed up to 80 bar pressure. Due to the lack of operational data found on Finnish gas transmission pipelines the estimation of hydrogen compatibility is not feasible. [18]

4 Welding of hydrogen pipelines

4.1 Basic principle of transmission pipeline welding

Hydrogen transmission pipe welding mainly considers the joining of pipe section by girth welds or the fabrication of pipe segments from steel plates by longitudinal or spiral welding. This thesis will focus on the former girth welding processes as it is recommended for hydrogen pipelines to minimize the amount of weld seams due to them acting as weak points for hydrogen embrittlement and material failure. [22]

The most common welding process is by fusion welding using an array of different equipment. Most used welding applications for carbon steel pipes are Shielded Metal Arc Welding (SMAW), Gas Tungsten Arc Welding (GTAW), Submerged Arc Welding (SAW), and Gas Metal Arc Welding (GMAW) or Flux Cored Arc Welding (FCAW). Most of these processes can be performed either manually or they can be automatized. During assembly the welding process is performed mostly by position welding. In some cases, roll welding is possible with a fully automatic welding process. [21]

According to ASME B31.12 (2014), welding with additional filler material requires groove welds in the joint design. These can be V, X or U-shaped grooves for butt welds. Whereas for socket welds it is required to produce a fillet weld. For no filler metals processes (Autogenous welding) the joint geometry shall be square-butt single welds. [22]

The circumferential butt welds of pipe components shall be complete weld joint penetration. These can be performed with backing rings, consumable inserts or as an open root condition [23]. However, according to the European Industrial Gases Association (EIGA, 2014) backing rings which remain in place are not allowed to ensure no interference with pipeline pigging, inspection and operations. [23]

Since hydrogen diffusion and embrittlement are strongly increased by surface and structural imperfections it is imperative to ensure a smooth and uniform finish on the inner surface of the weld seam [22]. EIGA instructs that in order to ensure a clean surface with minimal geometrical defects such as slag, beads or loose debris it is recommended to perform the root pass (i.e. the first weld pass at the bottom of the groove) with Gas tungsten Arc welding (GTAW). This is however only required for the root and therefore other previously mentioned welding processes are generally applicable for further passes required to finish the weld. The welding process can be made smoother with orbital TIG where the weld head orbits the stationary pipe. It can be automatic or mechanized performing with a consistent quality. [23]

4.2 Sources of hydrogen inclusion in welding processes

Even though hydrogen is included in almost all materials around us. The higher concentrated introduction of hydrogen to pipeline welds and heat-affected-zone (HAZ) during welding processes, combined with structural changes and residual stresses create a higher risk for hydrogen embrittlement and hydrogen induced cracking when in service and under cyclic loads.

High welding temperatures aide hydrogen molecules to format to atomic hydrogen. These sources for hydrogen can be ruled down to three major sources: Contaminants in the base and filler materials such as hydrocarbons like oil or cutting fluid. Moisture in the equipment such as the electrode covering or shielding gas as well as in the ambient environment. Products created by the decomposition of cellulosic-type electrode coatings and combustion products. [17]

4.3 Preventing Hydrogen inclusion and degradation risk

4.3.1 Preparation

The welding section should be cleaned of all debris and contaminants to prevent extra hydrogen inclusion. Grinding of the base material is allowed as well as thermal cutting if followed by mechanical preparation to ensure a smooth and slag-free surface without discoloration. The welding section should also be protected from environmental sources of hydrogen and contaminants such as all sources of moisture (rain, snow, ice) [22]. This can be mitigated by proper weld joint design, increased support for pipe sections for weight distribution and welding practises focusing in the minimization of these stresses. [17]

4.3.2 Heating

The welds metals composition and microstructure can be controlled to help minimize the risk of cracking. Since the highest risk of hydrogen cracking is with hard and/or brittle microstructures. It is important to take into consideration the heat gain and loss happening in the welding process. Faster cooling rates should be avoided to help prevent and mitigate the formation of martensitic or bainitic microstructures in the heat affected zone. According to ASME B31.12 the hardness of the metal is mainly influenced by the cooling rate from 800 to 500°C post-welding [22]. Causes for these faster cooling rates can be low heat input processes or improper interpass temperatures. [17]

It is noted that maximum interpass temperature for pipeline welding should be approximately 250°C. For steel with lower hardenability, such ones that are also recommended for hydrogen pipelines, the heat treatment has a greater role in preventing hydrogen embrittlement and cracking via affecting the formation of the microstructure. Heat treating of steel with higher hardenability have a lower impact on martensitic formation since it will almost always form due to high heat processes. [17]

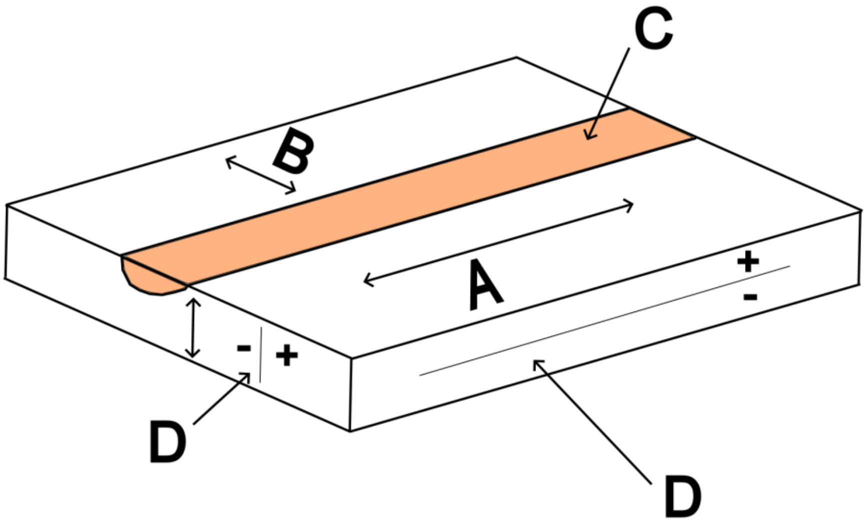

Figure 5: Residual stresses due to welding: A = longitudinal contraction; B = transversal contraction; C = weld bead; D = internal stresses. Based the sketch of Rogante et al. [24]

The residual stresses created by the pipeline welding should also be taken into consideration, since diffused hydrogen has been proven to have a tendency for pooling in areas of high stress concentration [14]. Heating the steel with proper pre-heating applications as well as controlling the temperature present in interpass welding is important. Heating applications recommended are induction heating coils or ceramic resistance heating bands. Post-welding it is recommended to perform a stress relief heat treatment to remove residual stresses still present in the material. [17]

4.3.3 Additive and pipeline materials

The moisture originating from the coated electrodes or fluxes can be mitigated by proper temperature baking and storage. These temperatures vary, but it is recommended by Lippold (2014) to use temperatures of 250°C to 450°C for baking and above 100°C for storage [17]. The use of low hydrogen welding rods at around 4ml/100g is recommended. DIN EN 12732 recommends that maximum SMAW stick electrode diameter should be considered for any given pipe wall diameters to control the heat created by the process as for larger electrodes a higher current is typically used. For a maximum wall thickness of 7mm, a 2.5mm electrode is recommended [16]. Previously mentioned cellulosic-type electrode coatings release a large amount of hydrogen during welding and therefore should not be used at all in hydrogen pipelines [17].

Pipeline steels for oil and gas transmission are typically X42-X80 grade low alloy carbon steels. It is, however, important to take into consideration the hardness of the steel to help mitigate hydrogen embrittlement failure mechanisms. The Finnish Safety and Chemical Agency (TUKES) notes that it is recommended to avoid the use of steel grades with higher hardness to lower the risk of hydrogen embrittlement. According to their safety guide it is recommended to use steel grades of SFS_EN ISO 3138 L360 or API 5L Grade X52 or lower strength steel grades for hydrogen transmission pipes [25]. Other steel grades have also been recognized as suitable for hydrogen service such as API 5L Gr. B, X42 and X60 [18]. Previously noted austenitic stainless steels, such as AISI 316L are generally applied to pressurized hydrogen service and are especially considered for corrosive environments for their durability [23].

EIGA recommends a maximum hardness for steels used in pipelines to be 22 HRC (Hardness Rockwell C) or 250 HB (Hardness Brinell). This is equivalent to a tensile strength of 116 ksi or around 800 MPa. It may be necessary for achieving acceptable weld zone hardness to use steel grades with even lower strength grades, since the fusion zone usually has a higher hardness than the base material and is therefore more prone to embrittlement. [23]

The Carbon Equivalent (CE) is also to be considered when choosing pipeline steels for steels with higher CE are more susceptible to hardening during welding heat cycles and runs the risk for higher formation of martensite. The most common formula for the calculating of CE for pipeline steels assesses how the alloying elements such as manganese, chromium, molybdenum, vanadium, nickel and copper affect the hardening of the steel with the carbon. The equation is as follows:

$$CE = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

EIGA states that for the fabrication of hydrogen pipelines the maximum CE allowed is 0.43 which is equivalent to API 5L Grade X52 pipeline steel [23].

4.3.4 Protection/shielding gases

Inert gases are recommended for the shielding of the weld arc and molten weld pool to prevent contamination from atmospheric gases. Inner weld surfaces can also be protected from slag deposits or porous surfaces created by rection with oxygen on the underside of welds with these gases. [23]

It is reasonable to assume, that shielding gases containing hydrogen should not be used, as previously mentioned by Lippold (2014), any excess sources of hydrogen shall be removed [17].

4.3.5 Cooling

Since almost all welds will eventually cool into the temperature range for Hydrogen cracking (-100°C to 200°C), ensuring proper cooling rate control can help preventing it by allowing the hydrogen introduced to the material by the welding process to diffuse out of the structure. This preventive mitigation of hydrogen pooling in the structure gives the steel more capacity for future diffusion of hydrogen via diffusion from the pipeline gas. [17]

4.3.6 Surface finish

To ensure a finished and clean inner surface and the removal of debris, several different methods exist. It is also possible to perform several of these to ensure the quality of the interior. Methods most used for cleaning are pigging, mechanical scraping and high velocity gas purge. Pigging is recommended as the primary choice for hydrogen pipelines. A pig is a cylindrical gadget designed to be pushed forwards with the pressure created by the flow of gas through the pipe. Several types of categories for pigs exist and can be divided into gauging, foam, rubber disc/cup, wire brush and scraper. It is necessary to take into consideration the materials used in a pig for it to be able to perform in a hydrogen environment. Gas purging generally refers to the use of high compressed gas as high speeds to remove contaminants. [23]

4.4 In-service welding

In-service welding refers to welding work performed on pipelines that are at some level actively operating and transmitting hydrogen gas while pressurized. Typical reasons for this are maintenance or branching lines.[16]

Hot-tapping refers to a procedure which requires a hole to be drilled into the side of a pipe without releasing gas into the environment. This is performed to create a junction in a pipeline. Generally requiring two half sleeves to be installed with one being a T-section for a latter instalment of the drilling unit and eventually, a pipe. The sleeves are connected to each other with butt welds, mechanically forced to sit tightly on the pipe and welded onto the pipeline with circumferential fillet welds. [16]

Another in service process requiring welding is needed for bypassing and shutting off damaged parts of a pipe by redirecting the flow through two sleeves with T joints connected to each other known as stoppling. Two other T joint sleeves are also installed with stopples in a section between the bypasses for a pressure-free work environment. [16]

Typical welding processes used are Shielded Metal Arc Welding and Gas Tungsten Arc welding. The additional pressurized and travelling hydrogen inside the pipe creates a unique challenge for welding work due to the higher susceptibility of increased hydrogen diffusion caused by heat and pressure (fig.6). [16]

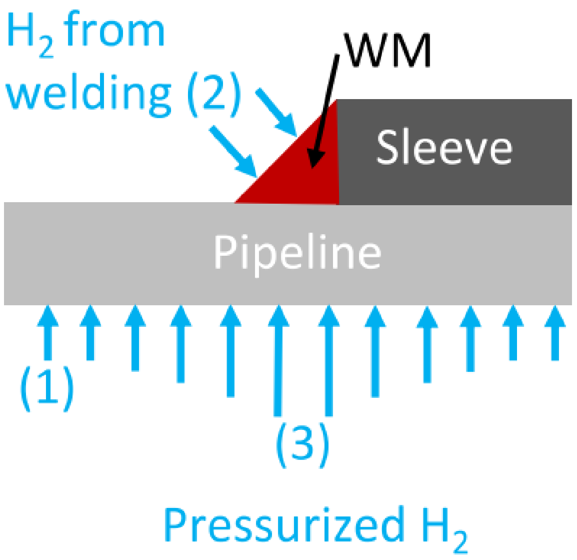

Figure 6: Hydrogen sources for in-service welding of sleeve installation. (1) hydrogen from pre-charged pipeline due to service, (2) during welding (consumables), (3) the additional hydrogen uptake from heated pipe surface. [16]

As mentioned before, hydrogen diffusivity increases in steel with temperature, creating higher concentration of hydrogen in the material and affecting thus the mechanical properties. The active flow of hydrogen in the pipe also affects the cooling rate of the welds, caused by the high heat convection of hydrogen thanks to its high heat capacity. As the gas flow rate in the pipe during transmission is potentially planned to be higher due the low volumetric density. These circumstances can speed up the cooling of the HAZ and creating a higher risk of more brittle microstructures to from. [16]

Temperature and flow control in the Heat Affected Zone is key to mitigate the hydrogen diffusion and the microstructural changes. The temperature of the welding process is also important for work safety due to the high flammability of hydrogen and hydrogen mixtures. Especially with air the ignition temperature can be as low as 500°C, grossly exceeded by welding temperatures. While the gas flow has a positive effect of lowering the heat on the surface of the pipe, reducing the risk of burn-through and potentially reducing the size of the HAZ, it is still recommended during welding processes to lower the operating pressure of the pipelines to ensure the proper cooling and heat treatment for the formation of the microstructure. [16]

4.5 Methods of observing welding-caused effects and quality (NDT)

Finished welds shall be examined to ensure a good quality of weld fabrication as well as to ensure the components are suitable for hydrogen operation and pose no risks of increased hydrogen diffusion or embrittlement/cracking. [23]

Methods for examination are vast, but it is generally recommended to perform non-destructive testing (NDT) of each weld. According to EIGA butt weld joints shall be fully radiographically examined as well as final closing welds. In situation where radiography cannot be performed due to other radiological hazards, ultrasonic testing can be used to substitute. [23]

Since fillet and socket welds cannot be suitably radiographed due to their complex geometry it is more advised to perform tests with dye penetrant or magnaflux examination. In magnetic particle testing disruptions in an artificially induced magnetic field indicate structural defects in the material, outlined usually with the use of fine iron particles that tend to gather at these points. It is however to be taken into consideration that these methods focus on the surface quality and do not give adequate information on the internal structure. [23]

To ensure the toughness of the pipe and that the microstructure of the pipe wall has not been affected by the heat cycles present in welding beyond acceptable levels, micro hardness tests can be performed with samples. [23]

Previously mentioned pigs can also be used to perform quality testing and observation of inner surfaces. So called “smart pigs” are equipped with sensors for detecting surface irregularities such as corrosion, dents, cracks or changes in the wall thickness. They use a variety of technologies such as ultrasonic testing. [23]

5 Special considerations for welding in Finland and hydrogen related risks

5.1 Effects of Finnish environment and soil conditions

5.1.1 Temperature and weather conditions

Due to Finland's wide range of seasonal temperatures and soil frost cycles, pipelines can be susceptible for increased mechanical strain created by the frozen moist soil expanding and creating ice lenses between ground layers pushing structures embedded in the ground. This process is known as a frost heave cycle. During thawing, the melting ice can create a weak base, saturated with water and weakly supporting structures embedded in it. The heterogeneity of soil bases and especially their ability to suck up water can create uneven expansions that in order can cause bending forces and axial stresses along pipelines. [26]

5.1.2 Sub-surface welding

Offshore pipelines are typically welded together on pipelay barges section by section, such as on land. To mitigate the bending stress on the pipe caused by the finished line rising from the seafloor to the surface, the angle of the weld section is either horizontal or vertical. Typical welding practises show that preheating of pipelines is even more imperative when welding at sea due to excessive moisture in the environment. [27]

In cases of repair, connecting pipelines to each other or creating junctions, underwater welding may be required. This is typically categorized to wet welding and dry environmental welding. Wet welding describes welding work performed in the open water. Presence of H_2O means high concentrations of hydrogen in the weld pool as well as fast cooling. The product is welds containing high levels of martensite and brittle microstructure. [27]

Dry environmental welding can be performed either at hyperbaric conditions matching the outside water pressure or at depressurized conditions matching atmospheric pressure. At high pressures the cooling rate is also elevated and therefore requires extra heating to control it. Hydrogen adsorption also increases with pressure; this can result with cooling in a reduction in critical crack stress limits. Welds done in an environment equivalent to atmospheric pressure have been noted to have a same level of quality and toughness as on land and therefore could be the primary process to ensure pipeline welds suitable for hydrogen operation [27].

5.2 Risks of hydrogen welding

5.2.1 Leakage

Hydrogen's permeation rate in pipelines is on average four to five times faster than methane, which constitutes most of the natural gas transmitted. Therefore, it is noted that hydrogen leakage from the pipeline is 1.3-2.8 times more likely when compared to methane and four times as high as for air (Tian et al., 2023). Simulation studies for hydrogen leakage have noted that due to hydrogens low density and high buoyancy, the accumulation of hydrogen at ground level was considered small. [28]

A notable risk for hydrogen leakage has been their potential transmission via repurposed NG pipelines. Originally not designed for hydrogen operation, they generally have thinner wall and a higher susceptibility for hydrogen induced failure mechanisms. [28]

Location, space and leakage rate generally contribute to the overall accumulation behaviour of gas. Leakage rate has been tested to increase when natural gas was mixed with hydrogen, however, it was considered only notable with blend rations higher than 50%. [28]

Since hydrogen is also odourless, it is difficult for operators to detect leaks without equipment increasing the safety risks. According to Lipiäinen et al. (2023). Earlier studies have concluded that no suitable odorants for hydrogen exist, as they are not light enough compared to hydrogen. However, this is contrasted by other experiments arguing that it is viable. The authors conclude that the odorization may be more viable for gas mixtures, rather than pure hydrogen. Some odorants, especially Sulphur, have also been noted to cause damage to hydrogen storages and fuel cells. Currently leaks are controlled with detectors installed on pipelines. [18]

5.2.2 Flammability and explosion risk

Gas accumulation, especially in a confined space is prone to explosion. According to EIGA hydrogen-air mixtures can ignite at relatively low temperatures when compared to other flammable gases. Hydrogen mixtures can require only 0.017mJ of energy for ignition, whereas for hydrocarbons in NG it is 0.25mJ. The risk for auto-ignition of leaks and atmospheric vents is very high for hydrogen, partially caused by hydrogens tendency to heat up when it expands moving from a higher pressure to lower. Burning hydrogen is especially dangerous due to the flames being almost invisible creating a higher risk for injuries. [23]

5.2.3 Burnthrough

During a welding process done on a pipeline that is actively pressurized and operating a risk of burnthrough is always to be considered. Burnthrough is caused by the decrease of a pipe walls material strength below the mechanical effect of the pressure created by the gas on the surface. This critical softening can result a blow out, squeezing the material out and causing an increased risk of explosion due to heat sources present. Such effects are mainly avoided with minimum wall thicknesses as mentioned by standards like DIN EN 12732. At the present time, specific minimum wall thicknesses have not been set for hydrogen transmission. [16]

6 Conclusions

Several hydrogen pipeline projects are currently planned to connect Finland’s future hydrogen economy to a reliable energy network that strengthens European energy supply and transition to net-zero emissions.

As hydrogen intake is affected by the combination of heat and pressure, transitioning from standard oil and gas pipelines requires changes in the core focus points in welding processes. While the mechanical strength of the welds is still critical, the major threat for pipeline integrity are the metallurgical changes caused by hydrogen intake and accumulation in the steel’s material structure.

As the intake rises due to geometrical defects and surface impurities, pristine quality welds must be produced with as little amount of hydrogen received from additive materials and the environment. However, this is more challenging with in-service pipelines due to the presence of extra hydrogen in the pipe. This can be controlled with pressure and velocity changes with regards to heating.

The heat cycles experienced by the pipe materials dictates the formation of the microstructure and the quality of the welds. Pre-heating and post-weld heat treatment are critical in removing excess hydrogen diffused into the welds and heat affected zone, while ensuring the material stays ductile and soft. Low temperatures during the winter and unusually high-pressure conditions in sub-sea pipelines can increase the risks of uncontrolled heat cycles during welding as the risk for fast cooling times increases.

Standard piping materials must be reconsidered as previously preferred high-strength steels have an increased risk of hydrogen induced cracking and embrittlement due to their higher levels of susceptibility to the forming of brittle microstructures and therefore lower tolerance for embrittlement. Lower-strength steel with increased softness and ductility such as API 5L X52 should be considered for the fabrication of pipelines.

Currently used natural gas pipelines in Europe use steels with varying hardnesses and wall thicknesses, which makes their assessment for repurposing a base-by-base case. The welds performed on these pipelines and the fatigue experienced by a lifetime of cyclic loading must also be scrutinized to ensure they can operate safely within a hydrogen environment.

Current reuses operate at a lowered pressure and flow rate to keep the material degradation in control, however, as hydrogens volumetric energy density is lower than natural gas, this proposes a logistical problem of matching the necessary energy demands.

More studies should be made for the longer-term service of hydrogen pipelines to determine more accurately the safe service life of these pipelines and the minimum quality and toughness of the welds.

References

[1] G. Erbach and L. Jensen, ‘EU hydrogen policy: Hydrogen as an energy carrier for a climate-neutral economy’, EPRS | European Parliamentary Research Service, PE 689.332, Apr. 2021.

[2] ‘REPowerEU’. Accessed: Mar. 31, 2026. [Online]. Available: https://commission.europa.eu/topics/energy/repowereu_en

[3] ‘Hydrogen’. Accessed: Mar. 31, 2026. [Online]. Available: https://energy.ec.europa.eu/topics/eus-energy-system/hydrogen_en

[4] ‘Renewable hydrogen - European Commission’. Accessed: Mar. 31, 2026. [Online]. Available: https://energy.ec.europa.eu/topics/eus-energy-system/hydrogen/renewable-hydrogen_en

[5] Clean Hydrogen Joint Undertaking., *Clean Hydrogen Partnership: success stories 2025.* LU: Publications Office, 2025. doi: 10.2843/1378857.

[6] L. Sivill *et al.*, ‘Hydrogen economy -Opportunities and limitations’, Prime Minister’s Office, Finnish Government (Prepared by AFRY Management Consulting Oy), 2022:41, 2022. [Online]. Available: https://urn.fi/URN:ISBN:978-952-383-068-4

[7] European Hydrogen Observatory, ‘The European hydrogen market landscape November 2024’, Nov. 2024. [Online]. Available: https://observatory.clean-hydrogen.europa.eu/sites/default/files/2024-11/The%20European%20hydrogen%20market%20landscape_November%202024.pdf

[8] Finnish Government (Valtioneuvosto), ‘Government resolution on hydrogen’, 2023:19, Mar. 2023. [Online]. Available: https://urn.fi/URN:ISBN:978-952-383-986-1

[9] Gasgrid Finland, ‘Nordic Hydrogen Route’, Gasgrid. Accessed: Mar. 31, 2026. [Online]. Available: https://gasgrid.fi/en/development/nordic-hydrogen-route-en/

[10] Gasgrid Finland, ‘Nordic-Baltic Hydrogen Corridor’, Gasgrid. Accessed: Mar. 31, 2026. [Online]. Available: https://gasgrid.fi/kehitys/nordic-baltic-hydrogen-corridor/

[11] Gasgrid Finland, ‘Baltic Sea Hydrogen Collector’, Gasgrid. Accessed: Mar. 31, 2026. [Online]. Available: https://gasgrid.fi/en/development/baltic-sea-hydrogen-collector/

[12] K. Mazloomi and C. Gomes, ‘Hydrogen as an energy carrier: Prospects and challenges’, *Renew. Sustain. Energy Rev.*, vol. 16, no. 5, pp. 3024–3033, Jun. 2012, doi: 10.1016/j.rser.2012.02.028.

[13] M. M. Hossain Bhuiyan and Z. Siddique, ‘Hydrogen as an alternative fuel: A comprehensive review of challenges and opportunities in production, storage, and transportation’, *Int. J. Hydrog. Energy*, vol. 102, pp. 1026–1044, Feb. 2025, doi: 10.1016/j.ijhydene.2025.01.033.

[14] Y. Zekun, Y. Zhanli, Y. Hao, Z. Yan, and X. Kai, ‘Hydrogen embrittlement in welded joints of high-strength pipeline steels: A review of mechanisms, characterization, and mitigation strategies’, *Int. J. Press. Vessels Pip.*, vol. 218, p. 105615, Dec. 2025, doi: 10.1016/j.ijpvp.2025.105615.

[15] R. Zhang *et al.*, ‘Gaseous hydrogen permeation of pipeline steels: A focused review’, *Renew. Sustain. Energy Rev.*, vol. 211, p. 115304, Apr. 2025, doi: 10.1016/j.rser.2024.115304.

[16] K. Erxleben, S. Kaiser, M. Rhode, T. Kannengiesser, and A. Kromm, ‘In-service and repair welding of pressurized hydrogen pipelines–a review on current challenges and strategies’, *Weld. World*, vol. 69, Aug. 2025, doi: 10.1007/s40194-025-02127-x.

[17] J. C. Lippold, *Welding Metallurgy and Weldability*. Newark, UNITED STATES: John Wiley & Sons, Incorporated, 2014. Accessed: Mar. 31, 2026. [Online]. Available: http://ebookcentral.proquest.com/lib/kutu/detail.action?docID=1840837

[18] S. Lipiäinen, K. Lipiäinen, A. Ahola, and E. Vakkilainen, ‘Use of existing gas infrastructure in European hydrogen economy’, *Int. J. Hydrog. Energy*, vol. 48, no. 80, pp. 31317–31329, Sep. 2023, doi: 10.1016/j.ijhydene.2023.04.283.

[19] B. S. Zainal *et al.*, ‘Recent advancement and assessment of green hydrogen production technologies’, *Renew. Sustain. Energy Rev.*, vol. 189, p. 113941, Jan. 2024, doi: 10.1016/j.rser.2023.113941.

[20] O. J. C. Huising and A. H. M. Krom, ‘H2 in an Existing Natural Gas Pipeline’, in *Volume 1: Pipeline and Facilities Integrity*, Virtual, Online: American Society of Mechanical Engineers, Sep. 2020, p. V001T03A057. doi: 10.1115/IPC2020-9205.

[21] A. Bahadori, *Oil and gas pipelines and piping systems: design, construction, management, and inspection*. Amsterdam, [Netherlands]: Gulf Professional Publishing, 2017.

[22] The American Society of Mechanical Engineers (ASME), *ASME B31.12-2014: Hydrogen Piping and Pipelines*, New York, NY., 2015.

[23] European Industrial Gases Association (EIGA), ‘Hydrogen Pipeline Systems’, EIGA, Brussels, IGC Doc 121/14, 2014. [Online]. Available: www.eiga.eu

[24] M. Rogante, P. Battistella, and F. Cesari, ‘Hydrogen interaction and stress-corrosion in hydrocarbon storage vessel and pipeline weldings’, *Int. J. Hydrog. Energy*, vol. 31, no. 5, pp. 597–601, Apr. 2006, doi: 10.1016/j.ijhydene.2005.05.011.

[25] ‘Vetyopas - Vedyn käsittelyn ja varastoinnin turvallisuus’, Turvallisuus- ja kemikaalivirasto (Tukes). Accessed: Mar. 31, 2026. [Online]. Available: https://tukes.fi/vedyn-kasittelyn-ja-varastoinnin-turvallisuus

[26] D.-S. Park, M.-B. Shin, W.-J. Park, and Y.-K. Seo, ‘Numerical Analysis of Frost Heave and Thaw Settlement for Pipeline Buried in Frost-Susceptible Soil via Thermosiphons’, *Appl. Sci.*, vol. 13, no. 3, p. 1948, Feb. 2023, doi: 10.3390/app13031948.

[27] A. C. Palmer and R. A. King, *Subsea pipeline engineering*, 2nd ed. Tulsa (Okla.): PennWell corp, 2008.

[28] X. Tian and J. Pei, ‘Study progress on the pipeline transportation safety of hydrogen-blended natural gas’, *Heliyon*, vol. 9, no. 11, p. e21454, Nov. 2023, doi: 10.1016/j.heliyon.2023.e21454.