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Use of existing gas infrastructure in European hydrogen economy

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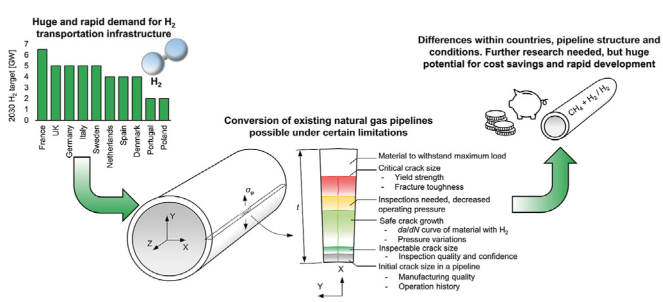
HIGHLIGHTS

- H_2 pipeline transportation projects in Europe were reviewed.
- Use of linear elastic fracture mechanics fatigue assessment tool was demonstrated.
- 80 bar natural gas pipeline could be converted to 45–55 bar H_2 pipeline.
- Existing natural gas network will be utilized for H_2 transportation in the future.
- Further research needed to ensure feasibility of H_2 transportation in existing grid.

GRAPHICAL ABSTRACT



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ABSTRACT

The rapidly increasing production volume of clean hydrogen creates challenges for transport infrastructure. This study improves understanding of hydrogen transport options in Europe and provides more detailed analysis on the prospects for hydrogen transport in Finland. Previous studies and ongoing pipeline projects were reviewed to identify potential and barriers to hydrogen transport. A fatigue life assessment tool was built because material challenges have been one of the main concerns of hydrogen transportation. Many European countries aim at utilizing existing gas infrastructure for hydrogen. Conducted studies and pilot facilities have provided promising results. Hydrogen reduces the fatigue life of the pipeline, but existing pipelines can be used for hydrogen if pressure variation is maintained at a reasonable level and the maximum operation pressure is limited. Moreover, the use of existing pipelines can reduce hydrogen transport costs, but the suitability of every pipeline for hydrogen must be analyzed, and several issues such as leakage, leakage detection, effects of hydrogen on pipeline assets and end users, corrosion, maintenance, and metering of gas flow must be considered. The

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development of hydrogen transport will vary within countries depending on the structure of the existing gas infrastructure, and on the future hydrogen use profile.

Introduction

Hydrogen and its derivatives are expected to play a significant role in the sustainable energy transition. Hydrogen can be considered a carbon neutral fuel when its production does not emit carbon dioxide (CO_2) emissions. It can be used as raw material, fuel, energy storage, and a substitute for imported natural gas in Europe [1,2]. Currently, hydrogen is used by the industrial sector, especially chemical and petrochemical industries. Hydrogen is mainly produced from natural gas by steam methane reforming (SMR) process or from coal by gasification [3]. Several European countries have published ambitious hydrogen strategies aimed at increasing the production of low-carbon or green hydrogen. For example, France, the United Kingdom (UK), Germany, Italy, and Sweden aim to have 5 GW or more of hydrogen production capacity by 2030 [4]. The expected increase in hydrogen production creates a great need to build an infrastructure for hydrogen transmission.

Hydrogen can be delivered to consumers as compressed or liquified form or using chemical carriers such as ammonia or liquid organic hydrogen carriers. The transport of compressed hydrogen via pipeline has been considered as the most cost-effective option for short distances (<3000 km) [5]. Currently, hydrogen is transported between hydrogen production facilities and industrial units via dedicated pipelines. There are approximately 5000 km of existing hydrogen pipelines in the world [6], and the oldest pipelines have operated for decades [7]. However, there is little experience on long-distance transport, and building of dedicated pipelines is expensive.

Europe has an advanced natural gas network in comparison to many other regions such as China [8]. Repurposing of existing pipelines is expected to result in significant savings compared to the building of new pipelines. Jens et al. [9] estimated that cost of repurposed pipelines could be 0.2–0.6 M€/km whereas the building of new pipelines could cost 1.4–3.4 M€/km. Hence, several European countries are interested in blending hydrogen to existing natural gas pipelines or repurposing the existing pipelines to transport 100% hydrogen [10–13]. Previous studies have claimed that up to 20 vol-% of hydrogen can be blended with natural gas in existing pipelines [14], but there is no one-size-fits-all solution for changing the operation of existing natural gas pipelines [15].

Previous studies have reviewed power-to-gas projects [16,17], investigated possible issues of the pipeline transport [18], and analyzed the compatibility of pipeline materials [19,20]. This study combines all the previous viewpoints and examine the prospects for hydrogen transport using existing natural gas pipelines in Europe. The study consists of a literature survey and a building of a pipeline fatigue life assessment tool. The purpose of the survey is to obtain an overview of the prospects for hydrogen transport in the European countries, understand the ongoing development, and find out the current possibilities and challenges. The material challenges have been identified as major issues in previous studies [15,21]. Thus, a pipeline fatigue assessment tool was built to provide information whether the use of the existing gas infrastructure is possible from a materials point of view.

The literature survey highlights the major differences in the natural gas network of the European regions, i.e., the Nordic countries, the Baltic countries, and the six largest European economies (Germany, the UK, France, Italy, Spain, and the Netherlands), and reviews the ongoing and planned hydrogen infrastructure projects. The study uses Finland as an example country for a more detailed analysis on the prospects for hydrogen transport. Finland represents a small natural gas user which can become an important hydrogen producer, and therefore the analysis provides new insights as many earlier studies has focused on the large European countries. The fatigue assessment tool uses a linear-elastic fracture mechanics (LEFM) -based approach and provides numerical analysis on transport capacity and allowed pressure variation. The study creates an overall picture of the current status and future of hydrogen transport and provides a basis for future studies.

Methods

Review on the existing gas infrastructure and ongoing projects

The state of the natural gas network infrastructure in selected European countries was mapped. The focus was on the network structure, but the future role of hydrogen was discussed as well. Most of the data was provided by national transmission system operators (TSOs).

The implemented, ongoing, and planned hydrogen pipeline transport projects in Europe were reviewed. Firstly, the study collected data on existing dedicated hydrogen pipelines, and then examined new pipeline transport options. Existing lists on the projects were used as a starting point for the review [16,17,22,23]. The aim was to include all implemented hydrogen projects that includes pipeline transport but part of projects that are still at the early phase and small-scale projects could be missing. Moreover, it is not always clear whether project plans have been implemented or whether the whole project has been cancelled. The review was conducted at the end of 2022. The field is currently developing rapidly, and interesting projects might have been launched after that.

The study aims at providing comprehensive information on the projects including data on operating years, network pressure levels, duration of the projects, blending rates, and sizes. Many projects do not report the important parameters and the outcomes in detail, making it difficult to compare the projects and draw the conclusions.

Linear-elastic fracture mechanics -based approach

The impact of hydrogen on the piping materials is considered as one of the main concerns in repurposing the existing infrastructure for hydrogen [24]. This study focuses on carbon steel transport pipelines, and the introduced approach cannot be directly applied for other materials such as plastics. Linear-elastic fracture mechanics (LEFM) -based approach was used to analyze transport capacity and the impact of pressure variation on the existing gas infrastructure. The fatigue crack growth can be estimated based on a load, which is mainly pressure fluctuation in case of pipelines.

The pressure induced hoop stresses in a pipeline can be estimated with Eq. (1).

$$\sigma = \frac{P \cdot OD}{2t}, \tag{1}$$

where

P Pressure [MPa]

OD Outside diameter [mm]

T Wall thickness [mm]

Pipeline inspection can reliably find cracks with 2 mm depth with pipeline inspection gauges (PIGs) by using non-destructive testing (NDT)-methods. The inspection length must be used as a base value for the initial crack length. The final crack size is estimated with fracture toughness K_{ic} values. According to the ASME B31.12, the minimum fracture toughness for hydrogen pipelines is 55 MPa $m^{1/2}$ in the hydrogen environment [25]. The pressure of hydrogen and the type of steel affect the values. The final crack size can be estimated with the evaluation of maximum pressure including safety factors and fracture toughness value in comparison to the stress intensity factor (SIF). The final crack size with 80 bar pressure according to K_{ic} values = 55 MPa $m^{1/2}$ is 6.3 mm whereas with literature based 100 MPa $m^{1/2}$ brittle fracture would occur with 8.3 mm crack size. However, a material strength limits the maximum pressure even when hydrogen exposure decreases the material toughness. Yielding occurs slightly before brittle fracture with X70 steel grades, selected pipeline dimensions, and literature values for fracture toughness in hydrogen environment. Consequently, an 8 mm final crack size was selected for fatigue performance analysis.

The SIF can be analytically calculated for edge cracks in plate as $F\Delta\sigma\sqrt{\pi a}$, where $F = 1.12$ and for semi-elliptical cracks like described in IIW recommendations [26] leading to slightly smaller SIFs. For this study DN500 pipeline was evaluated with Franc2D to increase results reliability (Fig. 1). With small initial crack size, the computational and analytical methods estimated similar SIF, whereas analytical equation returned non-conservative values for higher crack sizes.

Crack growth and corresponding fatigue strength can be obtained with one-stage Paris' law model (Eq. (2)).

$$\frac{da}{dN} = C\Delta K(a)^m \Rightarrow N = \int_{a_i}^{a_f} \frac{da}{C\Delta K(a)^m}, \tag{2}$$

where (units in mm and MPa)

N Fatigue life

$A_{i/f}$ Initial/final crack length

C Crack propagation parameter

M Slope parameter for crack propagation

ΔK Stress intensity factor range

ASME B31.12 [25] features a nonlinear correlation (in log-scale) between crack growth rate and SIF range. ASME B31.12 suggests a characteristic design da/dN curve for hydrogen pressure under 20 MPa (200 bar) (Eq. (3)).

$$\frac{da}{dN} = a1\Delta K^{b1} + \left[\left(a2\Delta K^{b2}\right)^{-1} + \left(a3\Delta K^{b3}\right)^{-1}\right]^{-1} \tag{3}$$

where $a1 = 4.0812\cdot10^{-9}$, $b1 = 3.2106$; $a2 = 4.0862\cdot10^{-11}$, $b2 = 6.4822$ and $a3 = 4.08810\cdot10^{-8}$, $b3 = 3.6147$, ΔK in MPa$\sqrt{m}$ and da/dN in mm/cycle.

In many cases, the crack propagation can be expressed with a two-stage model by mean or characteristic curves on test results. Consequently, the two-stage Paris' law model (Eq. (4)) can be used to describe the crack growth in the hydrogen environment. A lower limit of SIF should be taken into account, and the two-stage method should be modified to three stages with small SIF values with removing hydrogen effect on da/dN curves.

$$N = \int_{a_{i,1}}^{a_{f,1}} \frac{da}{C_1\Delta K(a)^{m_1}} + \int_{a_{f,1}}^{a_{f,2}} \frac{da}{C_2\Delta K(a)^{m_2}}, \tag{4}$$

where (units in mm and MPa)

$A_{i,1}$ Initial crack size at the first stage

$A_{f,1}$ Final crack size at the first stage and initial crack size at the second stage

$A_{f,2}$ Final crack size

Case Finland

The role of existing gas infrastructure in hydrogen transport has been studied by the gas industry in Europe and worldwide to some extent, but so far, the research from the Finnish perspective has been missing. This study investigates the role of the Finnish gas network in hydrogen economy looking at the structure of the network and the perspectives of the gas users. The emission reduction potential of hydrogen blending into the existing gas networks was estimated, and compared with national greenhouse gas emissions, which were 49 $MtCO_2$ in 2020 [27]. The consumption of natural gas in Finland is around 23.3 TWh [28]. The used densities and heating values for natural gas and hydrogen were 0.72 kg/m^2 and 50 MJ/kg, and 0.09 kg/m^2 and 120 MJ/kg [29,30]. Due to different gas properties, hydrogen addition reduces the volumetric energy density of the transported gas, and thus the obtained CO_2 emission reduction is lower than the blending rate [31].

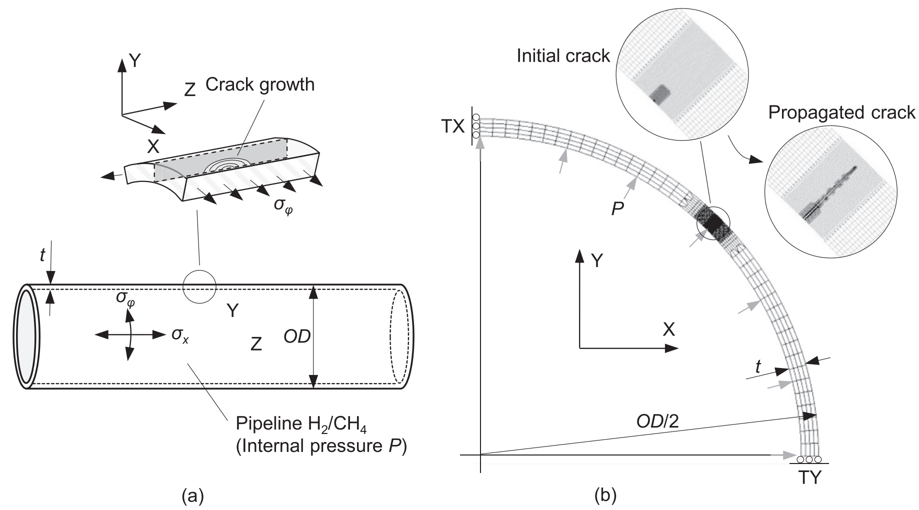

Fig. 1 – (a) Description of the studied pipeline geometry and crack, and (b) finite element model with loads and boundary conditions.

Results

Natural gas networks in Finland, the Nordic and Baltic areas, and Europe

The coverage of the natural gas network, the properties of pipelines, and the composition of gas vary significantly within the European countries. Fig. 2 presents the length of European natural gas transmission pipelines depending on maximum operating pressure, pipe diameter, and steel type. Transmission pipelines are typically made of steel, and plastic materials can be used in low-pressure distribution pipelines. 60% of European pipelines are made of steel types (API 5L Gr. B, X42, X52, and X60) which have been considered suitable for hydrogen blending [32]. Common API 5L Gr X70 steel (26% of European pipelines) and the rarer steel grades API 5L Gr X65 and X85 (2% of European pipelines) may cause more challenges (hydrogen embrittlement). The Russian natural gas is almost pure methane whereas European grades contain heavier hydrocarbons and nitrogen [33], which affects the Wobbe index and thus the hydrogen blending opportunities.

Gas accounts for approximately 6% of total final energy consumption in the Nordic countries, 18% in the Baltic countries, and 26% in Europe [34–37]. Gas use varies, e.g., many large European countries use natural gas as the main fuel in household heating and cooking, which is not the case in the Nordic and Baltic areas [38]. An overview of the natural gas grid in the Nordic and Baltic areas, and Europe is presented in Table A1. The coverage of the gas network varies significantly. Denmark is the only Nordic country that has a natural gas grid with good coverage, and the grid is connected to the European markets. In the Baltic countries, the natural gas grid has rather good coverage and the grid is connected with several surrounding countries. Natural gas infrastructure, including pipelines and storages, is highly developed in the large European countries [39], and the lengths of pipelines are high compared to the Baltic and especially the Nordic countries. The large European countries have a significant number of plastic distribution pipelines that should tolerate hydrogen [31], which is beneficial in comparison with many Nordic countries, when the potential for hydrogen transport is mapped out. For example, in the UK, 84% of distribution pipelines are made of plastic [13]. At least the Dutch gas

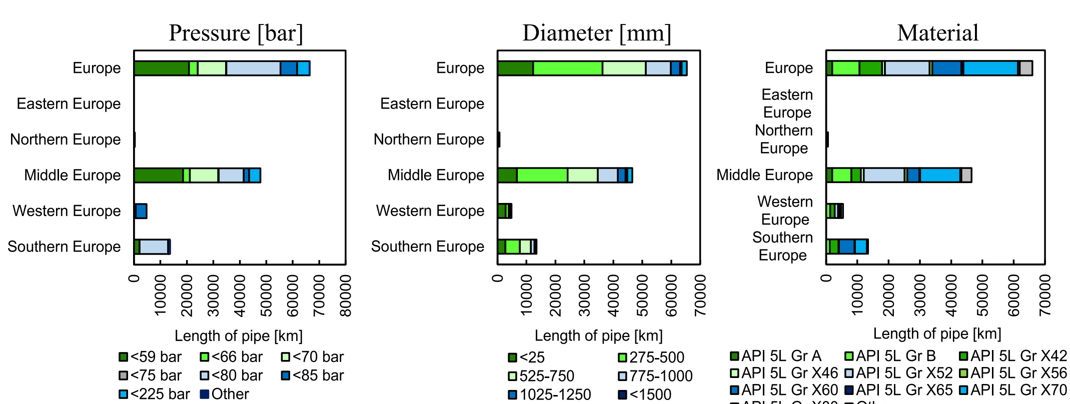

Fig. 2 – Length of European natural gas transmission pipelines depending on maximum operating pressure, pipe diameter and steel quality [32].

network consists of several parallel pipelines, and thus the country sees part of existing pipelines can rather easily be converted for 100% hydrogen [10].

The European countries have different futures as gas users. The Nordic countries could theoretically phase out most of the natural gas use, e.g., Finland halved its natural gas consumption in 2022 due to supply disruptions from Russia [40]. The large European countries have a huge demand for substitutes for natural gas, and hydrogen has been seen as an attractive option for several purposes. For example, the UK believes that hydrogen can play an important role in the heating of buildings and the blending of hydrogen into the existing grid may provide an intermediate solution for CO_2 emissions reduction [41]. The Nordic and Baltic countries are mainly interested in applications that often require the transport of 100% hydrogen, e.g., the Finnish and Swedish industry is interested in the utilization of 100% hydrogen [11,42]. Denmark is the only Nordic country that has studied and demonstrated the blending of hydrogen and natural gas. As a leading European natural gas producer, Norway is interested in producing blue hydrogen, but it has not been very active in developing its own hydrogen infrastructure [43].

Ongoing hydrogen pipeline transmission projects

Current state of hydrogen transport

At the moment, most of the hydrogen is produced and consumed at the same site, and only part of it is delivered to industrial plants via pipelines. Many of the existing pipelines have operated successfully for decades, at pressures up to 100 bar [44]. The diameters of the hydrogen pipelines are currently relatively small, approximately 100–300 mm [45]. The pipelines utilize typical pipeline steel grades such as API 5L X42/X52 steels but the wall thicknesses are larger than in case of natural gas pipelines [45]. The length of the dedicated pipelines is approximately 5000 km globally, and 60% of the pipelines are in the United States [6]. There are approximately 15 operational dedicated hydrogen pipelines with a total length of 1500 km in Europe [46]. The current pipelines deliver hydrogen to petrochemical and chemical industries.

The blending of hydrogen with natural gas and transporting the gas mixture via existing natural gas pipeline has been seen as an interesting opportunity in Europe. Currently, a part of European countries allows the blending of hydrogen, but the blending limits vary significantly within countries (Fig. 3). The restrictions are more legislative than technical limits. Many countries aim at increasing the limits in the future [47]. The natural gas network of the European countries is connected, and thus it would be important to have uniform rules for the use of hydrogen.

Pipeline projects

Many European countries see that the existing natural gas network will play a key role in hydrogen transport. The hydrogen projects in Europe are presented in Tables A2 and A3. Most of the implemented or ongoing projects inject only small amount of hydrogen into the natural gas grid (≤2 vol-%), but some projects have reached high blending rates (up to 20 vol-%), e.g., the Ameland in the Netherlands [50], the GRHYD in France [12], and the HyDeploy in the UK [51]. These projects

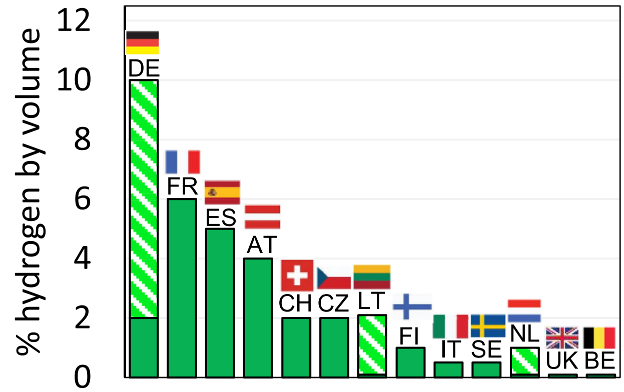

Fig. 3 – Current national limitations on hydrogen blending in gas networks in Europe. Higher limits apply under certain conditions. In Germany: if there are no CNG (Compressed natural gas) filling stations connected to the network, in the Netherlands: for high-calorific gas, in Lithuania: when pipeline pressure is higher than 16 bar. Data from Refs. [48,49].

did not utilize steel pipelines but plastic, copper, brass, and even rubber pipelines. The results of the HyDeploy project suggest that up to 20 vol-% hydrogen can be safely injected into the grid and hydrogen does not have effects on applications such as boilers, meters, or cookers. The Gasnetz Hamburg project blended up to 30 vol-% of hydrogen into the natural gas grid and delivered the gas for heating purposes [52]. They reported that the heat plant needed only minor modifications to adjust ignition times and burners. Most of the projects concentrate on natural gas distribution pipelines with a pressure range of 3.5 bar–16 bar. Many of the projects produce hydrogen for a certain purpose and the grid injection is a back-up solution. For example, the H2BER [53] and the Wind to Gas Energy Brunsbüttel [50] projects produce hydrogen for a filling station for cars. The Windgas Hassfurt [16] and the Hybrid Power Plant Enertrag [54] produce hydrogen to be combusted in a combined heat and power plant with natural gas. The units can inject a part of the hydrogen into the grid [53].

A couple of projects have injected hydrogen into high-pressure transmissions pipelines. Italy was the first European country that injected hydrogen into the transmission network: in 2019, 5 vol-% of hydrogen was blended into the natural gas grid and delivered to a pasta factory and a mineral water bottling plant [55]. Later, the share of hydrogen was increased to 10 vol-%. The WindGas Falkenhagen project in Germany injects hydrogen into the grid at 55 bar pressure [56]. The purpose of the project was to store and transport wind energy. The Energinet's project “Hydrogen Injection in the Gas Grid” in Denmark operates a pipeline between two gas stations with 12 vol-% of hydrogen mixed with natural gas [57]. The injection tests started in 2017, and no leakages have been observed so far. The HyNTS Hydrogen Flow Loop test for hydrogen in the UK operates an offline pipeline to test effects of 30 vol-% hydrogen on a DN300 X52 steel pipeline. The results showed minor changes in the steel during a 6-months trial, and it was suggested that hydrogen can be transported in existing pipelines without major problems. The Jupiter 1000 project in France includes hydrogen injection into the transmission grid, but no details were found on that project [58]. The reported results are promising, but the durations of the tests are short in comparison to the lifespan of a pipeline, leading to open questions on the long-term effects of hydrogen on a pipeline.

A couple of recent projects have studied repurposing existing pipelines to use 100% hydrogen. In the Netherlands, Gasunie converted a high-pressure (40 bar) natural gas pipeline into a hydrogen pipeline in 2018 [59]. The pipeline enables transporting hydrogen produced as a by-product in Dow Benelux to Yara. Denmark implemented the first project with hydrogen early, in 2007 [16]. 100% hydrogen was injected to a purpose build grid that delivered the hydrogen to 40 homes that produce electricity and heat with installed fuel cells. The H21 studies the use of 100% hydrogen for decarbonizing the energy system in the UK and the study includes some trials.

Several hydrogen transport projects in Europe are in a developmental phase. Many projects aim at building networks for 100% hydrogen using existing pipelines, and many projects target to complement the existing pipelines with new dedicated pipelines. Italy sees the role of the existing natural gas network significant in the transport of hydrogen. The TSO Snam aims to replace and develop the grid assets to be compatible with hydrogen, and they believe that even 100% hydrogen will be distributed via repurposed natural gas pipelines [55]. Snam claims that 99% of existing Italian network is ready to transport 100% hydrogen and 70% of network can do so without significant reductions of pressure [60]. Many hydrogen studies of the UK, such as the Hy4Heat [61] target to decarbonize the heating sector. As a leading Nordic country in developing green gas infrastructure, Denmark is interested in exporting hydrogen to Germany, and it plans a 350–450 km pipeline of which 50–60% could be repurposed pipelines [62]. Germany has ambitious plans for building a hydrogen grid that would consist of repurposed and new dedicated hydrogen pipelines. The Green Octopus Mitteldeutschland project that targets to build a 305 km dedicated hydrogen pipeline of which 190 km would be repurposed [63], is an example of the German projects. The Netherlands believes that it can build a 1400 km national hydrogen backbone utilizing 85% of repurposed pipelines [50]. The network would operate at 30–50 bar pressure that can be delivered by electrolysers and hence the network does not require compressors.

Hydrogen pipeline performance evaluation

Challenges of hydrogen transport

Despite ambitious plans and a few successful projects, hydrogen transport includes several factors that need to be addressed in order to secure safe operation, to meet end-users needs, and to maintain long lifetimes for both infrastructure and end-user applications. As the hydrogen economy is in its early phase and social acceptance plays a notable role in its development, there is no room for accidents or other major drawbacks.

Hydrogen can cause hydrogen embrittlement in pipelines meaning the degradation of steel, which can lead to cracking and even failure of the pipeline [15]. Measures including coating, use of inhibitors (O_2, CO, SO_2), and a pipe-in-pipe solutions have been suggested to enable reassignment of pipelines [64]. The coating provides protection against hydrogen embrittlement, but the coating of existing pipelines is practically extremely challenging. The use of inhibitors can protect against permeation, but inhibitors may be toxic, cause safety risks, and increase purity requirements of hydrogen. The pipe-in-pipe solution means adding hydrogen compatible pipe inside a pipeline, but this requires additional material and is challenging to implement in existing pipelines.

Fatigue of pipelines can be expressed as crack propagation which is caused by pressure fluctuations during the service life of the pipeline. The use of gas and the operation of pipeline compressors are the main reasons for the pressure variation. In case of natural gas pipelines, the fatigue of structures does not typically become a concern as the material strength limits maximum operation pressure. High strength steels (e.g. X100) enables a balance between high constant operating pressure and fatigue life. Increased pressure variation potential with high-performance pipelines highlights the fatigue performance which becomes more important aspect in design and through service life in the natural gas transmission lines. Drexler and Amaro [65] claims that fatigue is the expected failure mode in hydrogen pipelines as long as the pipeline operate below the specified minimum yield strength (SMYS), but fracture toughness test should be still performed.

Hydrogen is a small and reactive molecule. It tends to leak from small crack, seals, and joints of pipelines [14]. Thus, leakage detection is important for safety, but existing methods may cause challenges. Some earlier studies claim that there are no suitable odorants for hydrogen [18,66]. Existing odorants are not light enough to travel with hydrogen [66], and especially sulfur containing odorants are harmful to fuel cells and storages [67]. Therefore, current hydrogen pipelines mostly use detectors instead of odorants. However, there are conflicts in the literature: some studies argue that existing odorants can be used for hydrogen without problems [68–70]. Odorization may be easier with mixtures of natural gas and hydrogen than with 100% hydrogen.

Repurposing of existing pipelines would require modifications to existing assets such as valves and seals. The blending of hydrogen into the natural gas pipelines as well as operation of dedicated hydrogen pipelines may require improved maintenance and inspection procedures. Also, gas flow metering devices, compressors, and enduser applications may need modifications. Some gas users do not tolerate hydrogen and some of them require pure hydrogen, and thus gases need to be separated. Deblending is technically possible, e.g., using pressure swing absorption. The process currently consumes approximately 8–15 kWh/kgH_2 and costs around 5–7 €/kgH_2 [13]. Di Lullo et al. [71] claims that deblending route could be economically feasible only if hydrogen is recovered at low pressure. Moreover, as some end-user applications such as fuel cells require very pure hydrogen, compounds such as sulfur residues in natural gas pipeline could cause problems if an existing pipeline is converted for 100% hydrogen [15].

Hydrogen has a lower volumetric energy density than natural gas, making it difficult to achieve large energy flows in pipelines when using hydrogen. Earlier studies claim that approximately 70% of energy flow can be maintained when

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changing from natural gas to hydrogen [72]. Maintaining the energy flow requires a high compression power. It has been estimated that compression power must be threefold to maintain the flow rate when changing from natural gas to hydrogen [72]. Suitable compressors for hydrogen transport exists, but high diameters of natural gas pipelines can still cause challenges in case of repurposing [15].

Evaluation of current infrastructure on hydrogen transport

As presented in the previous section, the hydrogen transport includes various challenges. All the challenges cannot be addressed in detail in one study. In this study, linear-elastic fracture mechanics (LEFM) was applied for a fatigue strength assessment in order to enhance understanding of the effect of hydrogen on the existing natural gas pipelines. The initial crack length of pipelines is measured with NDT methods. The main purpose of LEFM analysis was to evaluate the suitability of current pipelines for hydrogen transport.

Hydrogen injection into the grid has been raised as an interesting possibility. However, knowledge on fatigue properties with low hydrogen partial pressure is still limited and pilot projects have been running only a relatively short period in comparison to the lifespan of pipeline systems. Nguyen et al. (2021) [73] evaluated the influence of hydrogen content on fatigue performance with 1 vol-% hydrogen blended with naturel gas in 10 MPa pressure with X70 pipeline steel. The evaluation was performed in a single stage with the smallest ΔK beyond 20 MPa $m^{1/2}$.1 vol-% mix significantly increased fatigue crack growth rate (FCGR) (Air $C = 2.06 \cdot 10^{12}$ ($m = 3.15$), 1 vol-% hydrogen $C = 1.26 \cdot 10^{11}$ ($m = 3.20$)). These values are well applicable to high pressure and stress ranges as the example pipeline initial crack size to tested ΔK values begins from 2 mm with 80 bar pressure range.

Chandra et al. [20] evaluated the impact of 1 vol-% and 10 vol-% hydrogen mixtures on X70 pipeline steel and weld areas. In the study, the total pressure of mix was 12.3 MPa and the partial pressures of hydrogen were 0.12 MPa, 0.62 MPa, and 1.24 MPa. The influence of partial pressure of hydrogen on the FCGR varies according to SIF (Fig. 4). The study found that ASME 31.12 *da/dN* curve is a suitable design curve for a hydrogen mix.

The local microstructure of the piping material and partial pressure of hydrogen were found to influence on the FCGR. The FCGR was up to 35 times faster in the hydrogen and natural gas mix than in the air in the most detrimental microstructure zone and SIF combination. Based on the obtained results, the minor content of hydrogen has a major influence on fatigue life. Hence, careful assessment of pipeline should be conducted before blending hydrogen with natural gas and during the service life.

The crack propagation parameter C and slope parameter m for a pipeline subjected to hydrogen can be evaluated performing fatigue tests in pressurized hydrogen environment similarly as in the air. Parameters for a 2-stage model were extracted from Baek et al. [74]: $C_1 = 3.9 \cdot 10^{16}$ with $m_1 = 8.5$ and $C_2 = 5 \cdot 10^{11}$ with $m_2 = 3.6$ with a knee point at $\Delta K = 11$ MPa$\cdot\sqrt{\text{m}}$. The values could be further evaluated by combining previous studies.

An outlook of *da/dN* curves used for a case analysis is illustrated in Fig. 4. Stress intensity factors for 30 bar and 80 bar pressure ranges are illustrated with arrows to connect SIF to

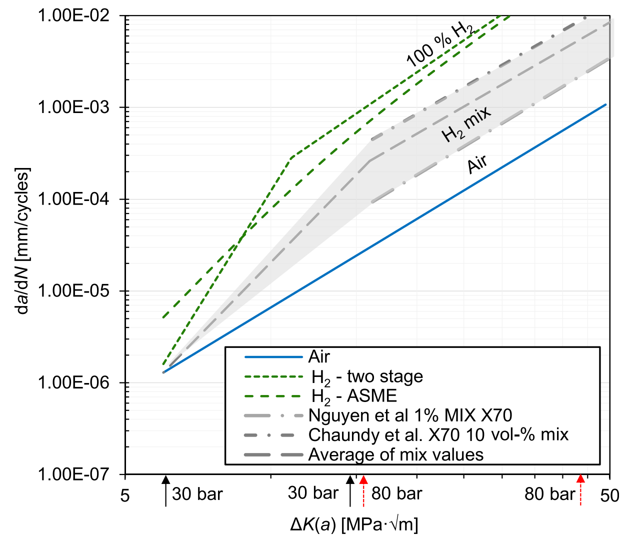

Fig. 4 — *da/dN* curves utilized in this study SIF values for 2 mm and 5 mm crack sized with 30 bar and 80 bar pressures.

crack size (2 mm black solid arrows and 5 mm red dashed arrows) with the case pipeline dimensions. *da/dN* curves for hydrogen mix are only a plot for constant section and first stage is estimated based on air and 100% hydrogen behavior. The behavior of hydrogen mix varies based on the partial pressure of hydrogen and the local microstructure. For methane and hydrogen mix, knee point of $\Delta K = 16$ MPa $m^{1/2}$was found reasonable, and influence of hydrogen on the FCGR was evaluated based on available data for ΔK values from 6 MPa to 16 MPa $m^{1/2}$.

The described method can be used to evaluate the suitability of steel pipelines for hydrogen mix or conversion of a pipeline for 100% hydrogen. Initially, the maximum operation pressure (MAOP) cycles can be used for the evaluation. A typical service life includes daily pressure fluctuations and significant pressure variations more infrequently. The pressure variation in gas pipelines and networks is influenced by the end-user demand and pipeline pressure increase in cyclic operation. In hydrogen pipelines, the leakage avoidance and possible storage should be considered with increased pressure range.

Case example on current infrastructure utilization on fatigue perspective

The fatigue life demonstration with the presented LEFM-based model is shown in Fig. 5. Natural gas pipeline fatigue life at the rated capacity is significantly higher than recommended fatigue life for hydrogen conversion (gray horizontal band in Fig. 5). The static strength against overloads and maximum operation pressure determines the capacity of natural gas pipelines. Consequently, the rated fatigue life can be shorter with hydrogen pipeline. A 2-stage model for 100% hydrogen ($\Delta K \geq 6$ MPa $m^{1/2}$ with 2 mm crack size) is applicable if the minimum pressure is 30 bar. Smaller pressure ranges would require a 3-stage model with removal of influence of hydrogen on FCGR. To utilize single stage crack growth parameters for methane and hydrogen mix ($\Delta K \geq 16$ MPa $m^{1/2}$

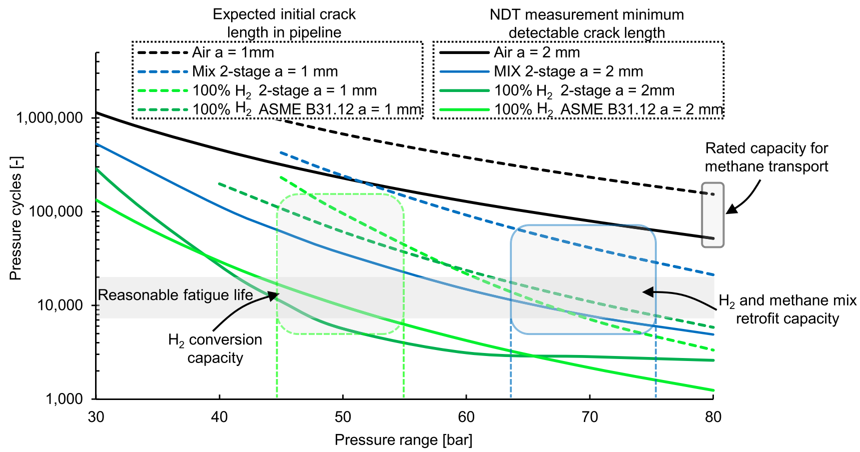

Fig. 5 – Fatigue life as a function of pressure range for DN500 t = 12.7 mm pipeline.

with 2 mm crack size) only the rated capacity (80 bar) of example pipeline was applicable. Thus, the 2-stage model with a *da/dN* curve illustrated in Fig. 4 was used for the analysis. Based on the LEFM analysis, the natural gas pipeline could be retrofitted to 65–75 bar mixed natural gas and up to 10% hydrogen transport line or converted to 45–55 bar 100% hydrogen pipeline. It should be noted that initial crack size of 2 mm is conservative assumption based on NDT detectable crack size with high probability. Dashed lines represent 1 mm initial crack size, which is a reasonable assumption for a pipeline.

The safety of pipeline transport of hydrogen against fatigue failure can be evaluated with the demonstrated procedure. When the estimated initial crack grows to upper limit of service value, the pipeline will be inspected. The pressure recording and evaluation with LEFM provides a tool for optimization of a pipeline use in respect to remaining fatigue life or the rate of decreasing service life.

Understanding of different crack lengths in a pipeline is crucial for fatigue strength assessment. An insight on crack growth and different phases is given in Fig. 6 together with most important factors in each step. The limits should be estimated in careful experimental and analytical methods especially when converting natural gas pipeline for hydrogen transport. With NDT inspection at pre-estimated and recorded pressure ranges modified intervals, the crack length and pipeline service life stage will be updated during its lifetime. Moreover, LEFM-based fatigue strength assessment has its limitations as it does not include e.g. corrosion in analysis. Due to its limitation in numerical evaluation, the importance of NDT-inspection should be highlighted in pipeline conversion pilots.

Case Finland: prospects for pipeline transport of hydrogen

Structure of natural gas network

The transmission network in Finland consists of 1150 km of high-pressure carbon steel pipelines and 60 km of low-pressure polyethylene pipelines [75]. Approximately 85% of the network consists of 54 bar pipelines, and less than 10% of the pipelines operates at up to 80 bar pressure. The diameter of the pipelines varies between DN100 and DN1000. The Finnish natural gas transmission infrastructure includes 8 gas turbine-operated compressors (54 MW in total) and one electricity-driven one with a capacity of 6.4 MW in four compressor stations in Imatra, Valkeala, Mäntsälä, and Inkoo. The length of the low-pressure (up to 4–8 bar) polyethylene distribution pipeline is 1997 km [28]. In addition to its own infrastructure, Finland has an offshore pipeline (Baltic Connector) to Estonia. The length, design pressure, and diameter of the pipeline are 77 km, 80 bar and DN500. There were no operational data available on the Finnish gas network, and thus the hydrogen compatibility cannot be evaluated using the introduced tool.

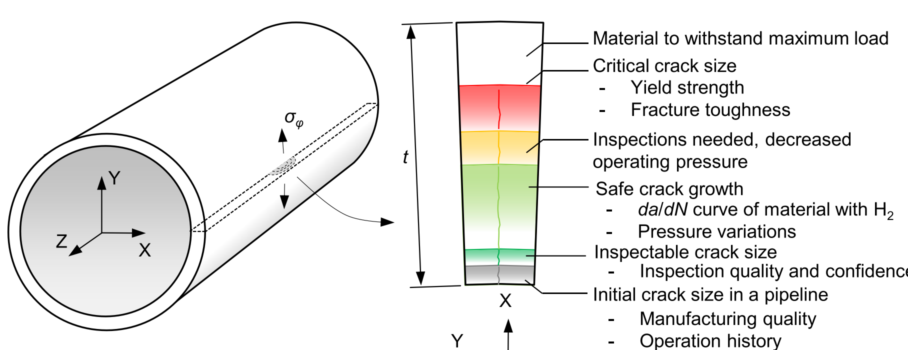

Fig. 6 – Schematic stages of crack growth in hydrogen pipeline and main influencing factors.

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End-users

The use of the current natural gas grid for hydrogen transport, i.e., the blending of hydrogen with natural gas or even repurposing the grid for 100% hydrogen, affects the end users. The consumption of natural gas in Finland by sectors is presented in Fig. 7.

The largest natural gas user in Finland is Neste oil refinery in Porvoo that uses natural gas for energy production and hydrogen production using the SMR process. The blending of hydrogen into the gas grid might be attractive for Neste refinery as hydrogen in natural gas improves the efficiency of the SMR process. However, the capacity of the production unit may not increase due to limitations of existing devices and this route may not be reasonable in a supply chain efficiency point of view. Forest industry, the second largest industrial natural gas user in Finland, uses gas in lime kilns, paper dryers and energy production. Hydrogen in natural gas changes combustion properties, e.g., flame velocity and temperature, but it can be expected that forest industry can manage the changes with small to moderate adjustments. Stora Enso Oulu already co-combust hydrogen in its lime kiln [76]. Many industrial sectors such as glass and ceramics manufacturing use natural gas for heating and the processes require a stable temperature. Therefore, fluctuations in the composition of gas may cause challenges. A small amount of natural gas is used for transport as CNG, which cannot tolerate higher than 2 vol-% of hydrogen [31]. Gas turbines can also be very sensitive to blended hydrogen. The blending of hydrogen into the gas grid in Finland provides limited benefits from the end-users perspectives but requires modifications and causes challenges. However, it can be expected that minor amounts of hydrogen could be safely injected into the gas network in case of a temporary oversupply of hydrogen in an electrofuel production unit.

CO_2 emissions reduction potential

The blending of hydrogen into the existing gas grid has a limited CO_2 emissions reduction potential in Finland (Fig. 8). 20 vol-% blending was considered as an upper limit for the share of hydrogen, and that case could lead to a 0.3 $MtCO_2/a$ reduction in emissions, which corresponds to 0.7% of national fossil CO_2 emissions. If the hydrogen had used for other purposes such as replacement of current fossil hydrogen use, the reduction of CO_2 emissions would be notably larger. Thus, when taking into account the risks and costs of hydrogen blending, it cannot be considered as an effective CO_2 reduction measure in Finland.

Future of hydrogen transport

There is a geographic mismatch between the gas network and the future production and use of hydrogen in Finland. The gas network covers southern Finland, but renewable electricity and consequently hydrogen production are expected to concentrate on the west coast. Thus, dedicated hydrogen pipelines are needed regardless of the potential of the existing network. Gasgrid Finland and Swedish Nordion Energy have a project called Nordic Hydrogen Route [77]. The project covers a 1000-km-long hydrogen pipeline from Örnsköldvik (Sweden) to Vaasa (Finland) that could serve an estimated 65 TWh hydrogen demand. The investment will amount approximately 3.5 billion euro and the pipeline should be in operation by 2030. Another planned project is a 15-km-long pipeline between Kemira's fertilizer plant in Joutseno and Ovako's steel mill in Imatra [78]. Finland has no ongoing hydrogen blending projects, but it has plans for dedicated hydrogen pipelines.

Based on this study, the blending of hydrogen into the gas network may not be an attractive solution in Finland.

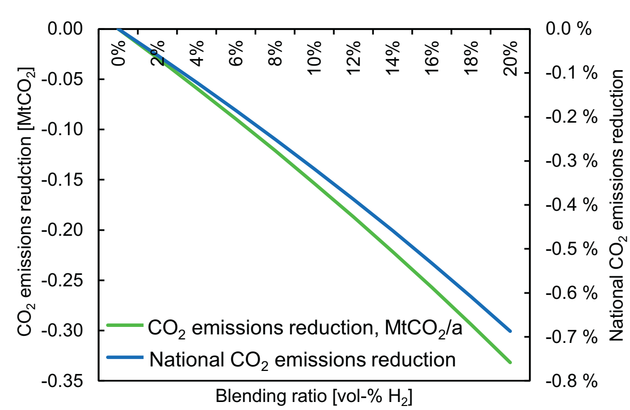

Fig. 8 – CO_2 emission reduction potential of hydrogen blending in Finland.

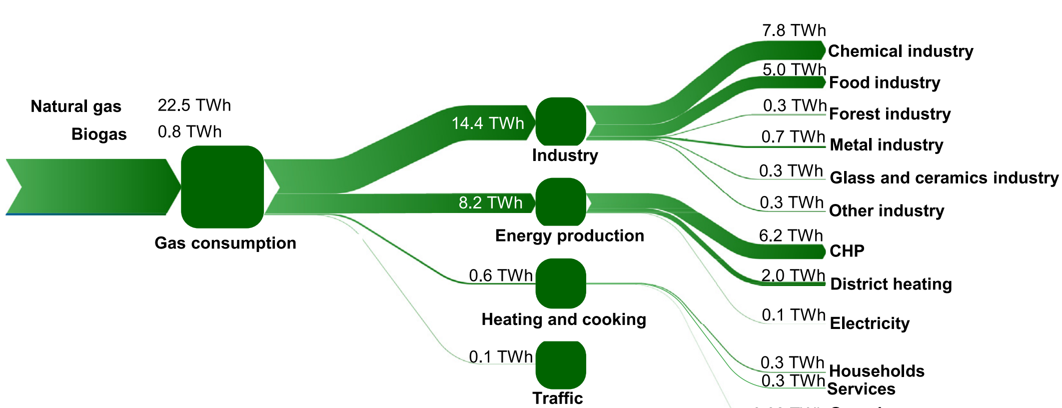

Fig. 7 – Natural gas consumption in Finland. Data from the Finnish Gas Association [28].

However, if the role of natural gas in the Finnish energy system continues to decline, a part of the network could be repurposed for 100% hydrogen. Based on our analysis, piping materials should not be a problem if pressure levels are limited, but the repurposing would require modification to pipeline assets. Moreover, several factors such as the age of the pipeline can affect the repurposing possibilities.

In addition to natural gas, the Finnish gas network is used for the transport of biogas. Biogas production in Finland is currently 1 TWh/a [79] and part of produced gas is injected into the transmission grid in Kouvola, Espoo, Lahti, and Riihimäki, and into the distribution grid in Hamina [75]. The biogas potential has estimated at 10 TWh/a [79], and thus Finland will most probably require infrastructure for the transport of biogas in the future. Additionally, many operators in Finland are interested in the production of e-methane. For example, Ren-Gas aims at producing 2.5 TWh of e-methane by 2030 [80]. The potential of the existing gas grid for the transport of renewable methane must be evaluated in further studies.

The use of the existing grid could be technically possible and lead cost savings. However, the potential for hydrogen transport utilizing the existing grids is considerably lower in Finland than in Europe. The prospects for hydrogen transport in Finland using the existing gas network are summarized in Fig. 9.

Discussion

The use of existing pipelines for hydrogen production in Europe is an attractive opportunity for several reasons. The blending of hydrogen into the gas grid has been considered as a transitional solution. Hydrogen decreases the CO_2 intensity of gas and can be delivered to customers without building expensive pipelines. The blending may play a role in electricity grid balancing and energy storage: hydrogen can be produced and injected into the grid when (renewable) electricity production exceeds consumption. Hydrogen can be processed to methane, which enables easy solution for the grid injection but causes efficiency losses. Despite the potential, the blending has disadvantages and uncertainties. Hydrogen is harmful to metallic materials in the infrastructure already in very small quantities, and different end users can handle varying percentages of hydrogen in natural gas. The future energy system will be more dependent on intermittent energy sources and it can be expected that hydrogen pipelines will need to operate with possible cyclic loads, creating additional challenges for materials [25]. When hydrogen is transported via the natural gas grid, some end users will require deblending, which is still costly. The blending has a limited CO_2 emissions reduction potential: the considered upper limit for hydrogen in natural gas, 20 vol-%, leads approximately to a 7% emission reduction [31], which is not much when urgent CO_2 emission reduction targets are considered. The future potential of the use of electrolysers for the electric grid balancing is still unclear. At the moment, electrolysers are expensive, and using them for responding to electricity surplus may lead to low operating hours and consequently long payback periods. Moreover, there is currently a huge demand for hydrogen, and the price for green hydrogen is considerably higher than for natural gas. The repurposing of the existing network for 100% hydrogen requires more modifications in pipeline assets and end-users operation than blending but serves end users that use hydrogen and may enable the reduction of the building costs of the future hydrogen network.

The building of dedicated hydrogen pipelines or repurposing existing natural gas pipelines is technically possible under certain limitations. There are still unsolved issues such as a chicken-and-egg-problem: hydrogen production will not scale up if there is no infrastructure, and infrastructure will not be built if there is not enough hydrogen production. Traditionally, a pipeline is built to serve the production and use at both ends of the line, and the building of pipeline requires enough commitments from the gas users. This has established the dedicated hydrogen transport system that exists today. The current situation is different as there is a will

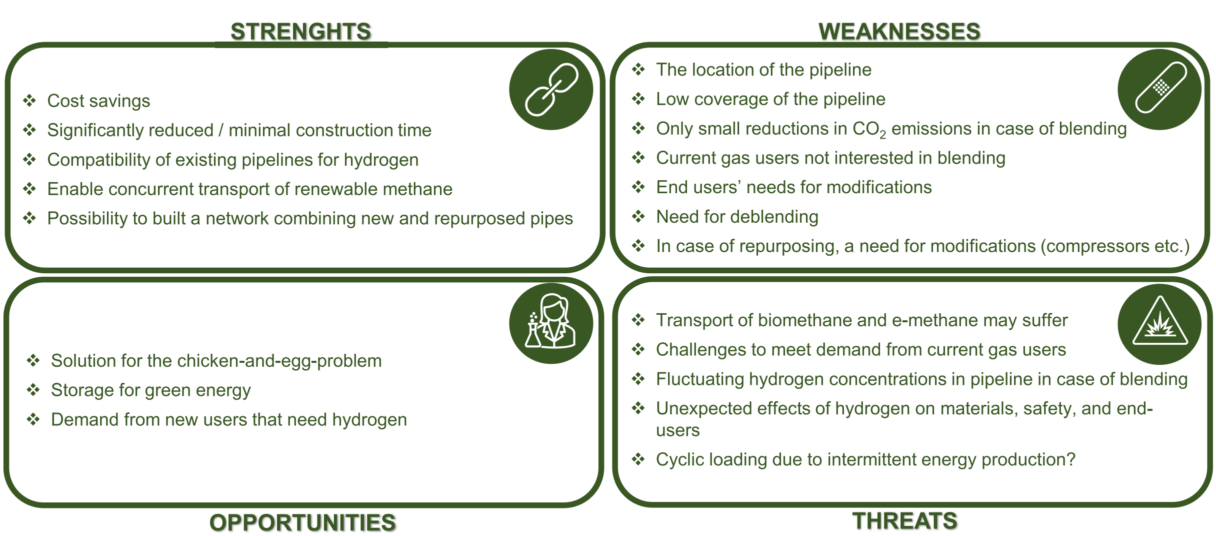

Fig. 9 – SWOT-analysis for the hydrogen transport in Finland utilizing existing gas network.

to construct a hydrogen grid that serves large areas and different users and producers. The pipeline infrastructure has so far emerged as a series of regulated monopolies known as gas TSOs. It is possible that TSOs will build the future pipelines if there is a market need or political will, i.e., funding. The building of a new pipeline can cost a couple of million euro per kilometer, e.g. [77], and therefore, it is an important question who will cover the costs.

The production and consumption of hydrogen can be expected to grow gradually. Pipelines have long lifespans and they need to serve high hydrogen production volumes in the future. However, scaling up the production will take time, and the transport of hydrogen via oversized pipelines will be very expensive in the case of dedicated pipelines. Therefore, it may not be reasonable to start construction of infrastructure by building large-scale pipelines, especially if the locations for future hydrogen users and producers are unclear. Repurposing of existing infrastructure, hydrogen valleys and possibly truck transport might serve the hydrogen economy until the production meets the volumes that are economically reasonable to transport via large pipelines.

Conclusions

Many countries have ambitious targets for hydrogen production, but infrastructure for hydrogen delivery is lacking. The transport of hydrogen in dedicated pipelines is mature technology at least for relatively short distances and moderate volumes, but the pipelines are expensive. The existing gas infrastructure will most probably play a role in the future hydrogen transport in Europe. Several research activities and ongoing projects aim at using the existing gas network for hydrogen transport to cut the costs and to provide a rapid solution for the chicken-and-egg-problem in hydrogen transport and production. The projects target to blend hydrogen into the natural gas network or repurpose existing pipelines for 100% hydrogen. Especially repurposing of parallel or unused pipelines have recognized as promising opportunities. Many studies claim that blending up to 20 vol-% of hydrogen into the existing natural gas grid does not require major modification to pipes or end-user applications. Our analysis suggests that existing pipelines can be used in hydrogen transport if the pressure range and maximum operation pressure are limited. However, the structure and materials of pipelines vary, and other aspects such as the effects of hydrogen on pipeline assets and end users as well as leak detection must be considered, and every pipeline must be carefully evaluated before repurposing. Additionally, there are conflicts in earlier studies in terms of limitations of pipeline transport of hydrogen, and it is possible that short trials do not provide information on a long-term effect of hydrogen on pipelines. More research and experiments are needed to fully confirm the hydrogen compatibility of pipelines and assets related to both transport and use. The prospects for the use of existing gas network for hydrogen in Finland are not as promising as in Europe due to the limited network coverage, the location of the network, and the gas use profile.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2023.04.283.

REFERENCES

[1] European commission. Brussels, Belgium: REPowerEU Plan; 2022.
[2] European commission. Brussels, Belgium: A hydrogen strategy for a climate-neutral Europe; 2020.
[3] International Energy Agency (IEA). Hydrogen supply. https://www.iea.org/reports/hydrogen-supply. [Accessed 11 October 2022].
[4] Sivill L, Bröckl M, Semkin N, Ruismäki A, Pilpola H, Laukkanen O, et al (In Finnish) Vetytalous – mahdollisuudet ja rajoitteet (Hydrogen economy – opportunities and barriers) 2022:69.
[5] European Commission. Assessment of hydrogen delivery options. 2021.
[6] S&P Global Commodity Insights. Hydrogen transport: moving molecules a core challenge for H_2 market growth 2020. https://www.spglobal.com/commodityinsights/en/market-insights/blogs/lng/012120-hydrogen-transport-moving-molecules-a-core-challenge-for-h2-market-growth. [Accessed 3 November 2022].
[7] Gillette JL, Kolpa RL. Overview of interstate hydrogen pipeline systems. Chicago: the USA; 2007.
[8] Zhang Q, Chen W, Ling W. Policy optimization of hydrogen energy industry considering government policy preference in China. Sustain Prod Consum 2022;33:890–902. https://doi.org/10.1016/j.spc.2022.08.017.
[9] Jens J, Wang A, van der Leun K, Peters D, Buseman M. Extending the European hydrogen backbone. Utrecht: the Netherlands; 2021.
[10] Tezel G, Hensgens R. HyWay 27 : hydrogen transmission using the existing natural gas grid? Final report for the Ministry of Economic Affairs and Climate Policy. the Netherlands: Amsterdam; 2021.
[11] Federal ministry for economic affairs and energy. Berlin, Germany: The national hydrogen strategy; 2020.
[12] Engie. The GRHYD demonstration project. 2022. https://www.engie.com/en/businesses/gas/hydrogen/power-to-gas/the-grhyd-demonstration-project.
[13] IEA Bioenergy. Renewable gas – hydrogen in the grid40. Germany: Darmstadt; 2021.
[14] Parfomak P. Pipeline transportation of hydrogen. The USA: regulation, research, and policy; 2021.

[15] European Union Agency for the Cooperation of Energy Regulators. Transporting pure hydrogen by repurposing existing gas infrastructure: overview of existing studies and reflections on the conditions for repurposing. Slovenia: Ljubljana; 2021.
[16] Quarton CJ, Samsatli S. Power-to-gas for injection into the gas grid: what can we learn from real-life projects , economic assessments and systems modelling? Renew Sustain Energy Rev 2018;98:302–16. https://doi.org/10.1016/j.rser.2018.09.007.
[17] Thema M, Bauer F, Sterner M. Power-to-Gas : electrolysis and methanation status review. Renew Sustain Energy Rev 2019;112:775–87. https://doi.org/10.1016/j.rser.2019.06.030.
[18] Melaina MW, Antonia O, Penev M. Blending hydrogen into natural gas pipeline networks. Colorado, the USA: A review of key issues; 2013.
[19] Wang Y, Yang X, Sun M, Ma L, Li X, Shi L. Estimating carbon emissions from the pulp and paper industry: a case study. Appl Energy 2016;184:779–89. https://doi.org/10.1016/j.apenergy.2016.05.026.
[20] Chandra A, Thodla R, Prewitt TJ, Matthews W, Sosa S. Fatigue crack growth study of X70 line pipe steel in hydrogen containing natural gas blends. Am Soc Mech Eng Press Vessel Pip Div PVP 2021;4. https://doi.org/10.1115/PVP2021-61821.
[21] Cerniauskas S, Jose A, Junco C, Grube T. Options of natural gas pipeline reassignment for hydrogen : cost assessment for a Germany case study, 1; 2020.
[22] International Energy Agency (IEA). Hydrogen project database. 2022. https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database. [Accessed 7 November 2022].
[23] Vartiainen V. Screening of power to gas projects. LUT University Lappeenrata, Finland; 2016.
[24] Penchev M, Lim T, Todd M, Lever O, Lever E, Mathaudhu S, et al. Hydrogen blending impacts study. the USA: California; 2022.
[25] The American Society of Mechanical Engineers. Asme B31.12-2019: hydrogen piping and pipelines. 2019.
[26] Hobbacher AF. Erratum to: recommendations for fatigue design of welded joints and components. 2019. https://doi.org/10.1007/978-3-319-23757-2_8.
[27] Statistics Finland. Statistics Finland's PxWeb databases 2022. http://pxnet2.stat.fi/PXWeb/pxweb/en/StatFin/StatFin__ene__tene/. [Accessed 15 September 2020].
[28] Finnish Gas Association. Kaasu suomessa (gas in Finland). (In Finnish) 2022. https://www.kaasuyhdistys.fi/kaasu-suomessa/tilastot/ [Accessed 21 January 2023].
[29] Engineering Toolbox. Fuels - higher and lower calorific values. 2023. https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html. [Accessed 5 January 2023].
[30] Engineering Toolbox. Gases - densities. 2023. https://www.engineeringtoolbox.com/gas-density-d_158.html. [Accessed 5 January 2023].
[31] Bard J, Gerhardt N, Selzam P, Beil M, Wiemer M, Buddensiek M. The limitations of hydrogen blending in the European gas grid. Germany: Berlin; 2022.
[32] Walter M, Bollien A, Sanchez-Lainez J, Schülken H, Cerezo Alarcón A, Gil V, et al. Hydrogen in gas grids: a systematic validation approach at various admixture levels into high-pressure grids. 2021.
[33] Finnish Gas Association (In Finnish). In: Maakaasukäsikirja (Natural gas handbook). Helsinki, Finland: Finnish Gas Association; 2014.
[34] Nordic Energy Research. The nordics: similar but different. 2018. https://www.nordicenergy.org/figure/similar-but-different/. [Accessed 14 November 2022].
[35] International Energy Agency IEA. Paris, France. Energy policies of IEA countries: Estonia 2019 review. 2019.
[36] International Energy Agency (IEA). Lithuania 2021 energy policy review. France; 2021.
[37] International Energy Agency (IEA). Latvia 2022. https://www.iea.org/countries/latvia. [Accessed 3 November 2022].
[38] Bertelsen N, Vad Mathiesen B. EU-28 residential heat supply and consumption: historical development and status. Energies 2020. https://doi.org/10.3390/en13081894.
[39] Lustenberger P, Schumacher F, Spada M, Burgherr P, Stojadinovic B. Assessing the performance of the European natural gas network for selected supply disruption scenarios using open-source information. Energies 2019;12:4685.
[40] Gasgrid. Transparency and market information. 2022. https://gasgrid.fi/en/gas-market/market-information/. [Accessed 8 December 2022].
[41] HM government. UK: UK hydrogen strategy; 2021.
[42] Fossil free Sweden. Sweden: Strategy for fossil free competitiveness: Hydrogen; 2021.
[43] Norwegian ministry of petroleum and energy, Norwegian ministry of climate and environment. Norway. The Norwegian Government's hydrogen strategy: towards a low emission society. 2020.
[44] Air Liquide. Questions and issues on hydrogen pipelines: pipeline transmission of hydrogen. 2005.
[45] Wang H, Tong Z, Zhou G, Zhang C, Zhou H. Research and demonstration on hydrogen compatibility of pipelines : a review of current status and challenges. Int J Hydrogen Energy 2022;47:28585–604. https://doi.org/10.1016/j.ijhydene.2022.06.158.
[46] Fuel cells and hydrogen ObservatorY. Hydrogen pipelines. 2022. https://www.fchobservatory.eu/observatory/technology-and-market/hydrogen-pipelines. [Accessed 3 November 2022].
[47] Agency for the Cooperation of Energy Regulators (ACER). NRA survey on hydrogen , biomethane , and related network adaptations evaluation of responses report. 2020.
[48] International Energy Agency (IEA). Limits on hydrogen blending in natural gas networks, 2018. 2022. https://www.iea.org/data-and-statistics/charts/limits-on-hydrogen-blending-in-natural-gas-networks-2018#. [Accessed 3 November 2022].
[49] Staffell I, Dodds P, Scamman D, Abad AV, Dowell N Mac, Ward K, et al. The role of hydrogen and fuel cells in the future energy systems. London, UK. 2017. https://doi.org/10.13140/RG.2.2.28890.13762.
[50] International Energy Agency (IEA). Global hydrogen review. France; 2022.
[51] HyDeploy. Pioneering the safe use of blended hydrogen in gas networks to reduce carbon emissions. 2022. https://hydeploy.co.uk/.
[52] Czechanowsky T. Hamburg's gas grid can handle 30 per cent hydrogen. 2022. https://www.energate-messenger.com/news/225464/hamburg-s-gas-grid-can-handle-30-per-cent-hydrogen. [Accessed 4 November 2022]. accessed.
[53] McPhy. On-site hydrogen production for the first total hydrogen station in Europe. 2019. https://mcphy.com/en/achievements/power-to-gas-en/h2ber/. [Accessed 4 November 2022] [Accessed 4 November 2022].
[54] Enertrag. Enertrag hybrid power plant. Germany: Brief description; 2009.
[55] Snam. Snam and hydrogen. 2022. https://www.snam.it/en/energy_transition/hydrogen/snam_and_hydrogen/ [Accessed 4 November 2022].
[56] Patel S. WindGas Falkenhagen: pioneering green gas production. 2020. https://www.powermag.com/windgas-falkenhagen-pioneering-green-gas-production/ [Accessed 4 November 2022].

[57] Energinet. Danish gas system able to store wind energy. 2019. https://en.energinet.dk/About-our-news/News/2019/05/21/Danish-gas-system-able-to-store-wind-energy. [Accessed 3 November 2022].
[58] Jupiter 1000. First industrial demonstrator of power to gas in France. 2022. https://www.jupiter1000.eu/english. [Accessed 5 December 2022].
[59] Gasunie. Gasunie Hydrogen pipeline from Dow to Yara brought into operation. 2018. https://www.gasunie.nl/en/news/gasunie-hydrogen-pipeline-from-dow-to-yara-brought-into-operation. [Accessed 7 November 2022].
[60] Snam. Italy. Snam 2030 vision and 2021–2025 plan. 2021.
[61] Hy4Heat. Hy4Heat 2022. https://www.hy4heat.info/. [Accessed 23 January 2023].
[62] Energinet. Energinet and Gasunie publish pre-feasibility study on hydrogen infrastructure. 2021. https://en.energinet.dk/Gas/Gas-news/2021/04/27/GUD-rapport. [Accessed 3 November 2022].
[63] Ontras Green Octopus Mitteldeutschland – grüner Wasserstoff für Industrieregionen (Green Octopus Central Germany - green hydrogen for industrial regions). 2022. https://www.ontras.com/de/go. [Accessed 5 November 2022].
[64] Cerniauskas S, Jose A, Junco C, Grube T, Robinius M, Stolten D. Options of natural gas pipeline reassignment for hydrogen : cost assessment for a Germany case study. Int J Hydrogen Energy 2020;45:12095–107. https://doi.org/10.1016/j.ijhydene.2020.02.121.
[65] Drexler E, Amaro R. Fatigue crack growth rates of API X70 pipeline steels in pressurized hydrogen gas compared with an X52 pipeline in hydrogen service. Int Hydrog Conf (IHC 2016) Mater Perform Hydrog Environ 2017:210. https://doi.org/10.1115/1.861387_ch22. –8.
[66] International energy agency (IEA). Paris, France: Energy technology perspectives 2012; 2012.
[67] Kopasz JP. Fuel cells and odorants for hydrogen. Int J Hydrogen Energy 2007;32:2527–31. https://doi.org/10.1016/j.ijhydene.2006.11.001.
[68] Murugan A, Bartlett S, Hesketh J, Becker H, Hinds G. Work package 2. UK: Hydrogen odorant; 2020.
[69] Polman E, Vlap H. Odorisation of hydrogen. The Netherlands: Stability of odorants in hydrogen; 2022.
[70] Vlap H. The Netherlands Odorisation: influence of sulfur containing odorant on end use appliances 2021:3–12.
[71] Di Lullo G, Giwa T, Okunlola A, Davis M, Mehedi T, Oni AO, et al. Large-scale long-distance land-based hydrogen transportation systems: a comparative techno-economic and greenhouse gas emission assessment. Int J Hydrogen Energy 2022;47:35293–319. https://doi.org/10.1016/j.ijhydene.2022.08.131.
[72] Björck P-O, Grahn M. A feasibility study of hydrogen distribution in present natural gas pipeline systems. Sweden: Gothenburg; 1999.
[73] Nguyen TT, Heo HM, Park J, Nahm SH, Beak UB. Fracture properties and fatigue life assessment of API X70 pipeline steel under the effect of an environment containing hydrogen. J Mech Sci Technol 2021;35:1445–55. https://doi.org/10.1007/s12206-021-0310-0.
[74] Baek UB, Nahm SH, Kim WS, Ronevich JA, San Marchi C. Compatibility and suitability of existing steel pipelines for transport of hydrogen-natural gas blends. Hamburg, Germany: Int. Conf. Hydrog. Saf.; 2017. p. 1–8.
[75] Gasgrid. Kaasun siirtoverkosto (Gas transmission network) (In Finnish) 2022. https://gasgrid.fi/kaasuverkosto/kaasun-siirtoverkosto/?fbclid=IwAR3huy6CsiF2Y5VjH_tx9Ygo1u_3tKUtetg49gil3NktGg0TYxR-rM_GCs4 [Accessed 22 January 2023].
[76] Pöyry Finland Oy (In Finnish). Oulu, Finland. In: Stora enso oyj oulun tehtaan tuotantosuunnan muutos (conversion of production in stora enso Oulu mill); 2018.
[77] Gasgrid. Nordic hydrogen route. 2022. https://gasgrid.fi/hankkeet/nordic-hydrogen-route/.
[78] Schönberg, K (In Finnish). Gasgrid Finland haluaa rakentaa Suomeen jättimäisen putkiston kuljettamaan vetyä (Gas transmission company Gasgrid Finland wants to build a huge hydrogen pipeline to Finland. 2022. https://yle.fi/uutiset/3-12482426.
[79] Gasum. Biogas is plentiful and its production capacity is yet to reach its full potential. 2022. https://www.gasum.com/en/insights/sustainable-traffic/2022/biogas-is-plentiful-and-its-production-capacity-is-yet-to-reach-its-full-potential/. [Accessed 5 January 2022].
[80] Ren-gas. Ren-gas. 2023. https://ren-gas.com/en/. [Accessed 20 January 2023].

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