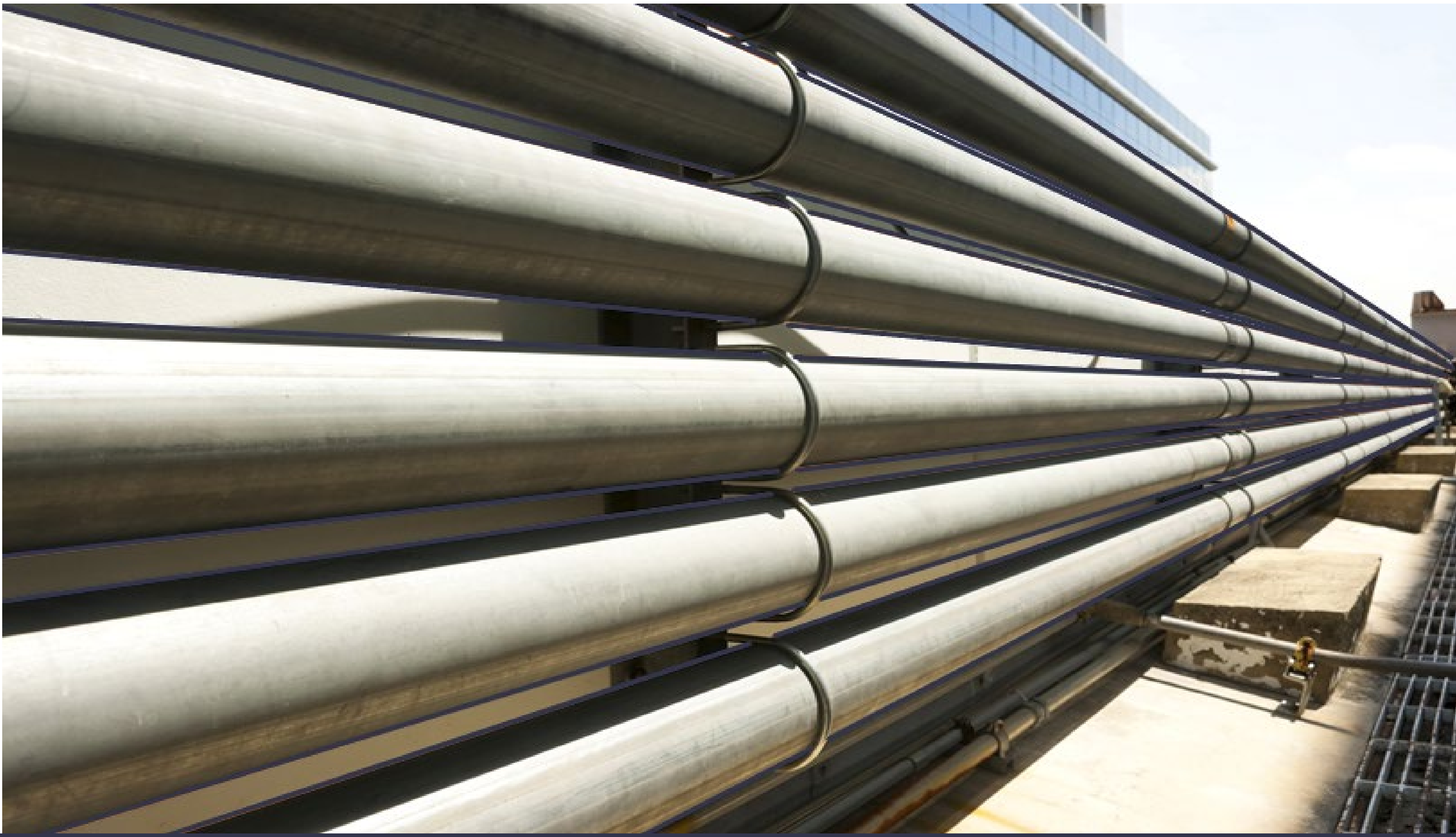
U.S. Department of Transportation (USDOT) Pipeline and Hazardous Materials Safety Administration (PHMSA)
Final Report No. 25-30994-6000754R

Evaluation of Analyses for Different Hydrogen/Natural Gas Blends

Michiel P. Brongers, PE
June 23, 2025



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to

U.S. Department of Transportation (USDOT) Pipeline and Hazardous Materials Safety Administration (PHMSA)

On

June 23, 2025

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Executive Summary

Hydrogen (H_2) gas concentrations between 1 and 20% are most proposed for blending, and such concentrations have been used in pilot projects worldwide. The pipeline industry is also interested in higher concentrations. H_2 blending is a complex challenge involving social, economic, and technical considerations. Various research organizations, industry organizations, commercial entities, and communities have contributed to the knowledge developed to date. However, each project has its particular focus and objectives. Combined research is not readily available.

The objective of this review was to describe how different H_2/natural gas (NG) blends affect pipeline integrity management intervals.

The following conclusions were formulated based on the results:

1. Laboratory testing shows that exposure to H_2-blended NG has a detrimental effect on the material properties of pipeline steels. The extent to which these effects affect pipeline integrity has not been fully studied, particularly for high-stress pipelines.

2. No lower bound has been established in laboratory testing where H_2 blending has been found not to have a detrimental effect on material properties.

3. Global practical experience with blended H_2/NG of different concentrations shows that using H_2-blended gas is feasible and that the detrimental effects of H_2 on steel may not greatly impact pipeline integrity. This experience is based on low-stress and distribution pipelines. More experience needs to be established with H_2 blending on high-stress pipelines. However, the fatigue life of defects in pipelines carrying H_2/NG may be shorter than for NG alone, warranting a shorter reinspection interval for those pipelines.

4. Based on a review of databases and other sources with information on H_2-related incidents and accidents, H_2 production and distribution pilot projects, blending facilities, and pipelines to transport H_2-containing gas blends, there were no counter-indications toward the successful use of H_2/NG blending. However, most project descriptions provided little technical information.

5. In the absence of shared integrity management, component performance, and material property data from operators who have run pilot or small-scale projects with blended H_2/NG systems, it is not possible to reliably estimate the remaining life of such systems with postulated or known flaws.

Table of Contents

List of Tables

List of Figures

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List of Acronyms and Abbreviations

ACES	Advanced Clean Energy Storage
AEM	Anion Exchange Membrane (Electrolyzer)
AGL	(India) Avantika Gas Limited
AGN	Australian Gas Networks
API	American Petroleum Institute
ARC	Anteater Recreation Center
ARENA	(Australia) Australian Renewable Energy Agency
ARIA	Analysis, Research, and Information on Accidents (Database)
BARPI	(France) Bureau for Analysis of Industrial Risks and Pollutions
CCGT	Combined-Cycle Gas Turbine
CCS	Carbon Capture and Storage
CFR	Code of Federal Regulations
CGD	City Gas Distribution
CGR	Crack Growth Rate
CP	Cathodic Protection
CPUC	California Public Utilities Commission
CRG	Catalytic Rich Gas
CSB	(U.S.) Chemical Safety Board
CTOD	Crack Tip Opening Displacement
DCVG	Direct Current Voltage Gradient
DESNZ	(U.K.) Department of Energy Security and Net Zero
DEU	(U.S.) Dominion Energy Utah
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
D/S	Downstream
DST	Decision Support Tool
DVGW	(Germany) Deutscher Verein des Gas- und Wasserfaches e.V.
EC	European Commission
ECA	Engineering Critical Assessment
EERE	(Office of) Energy Efficiency and Renewable Energy
EH2B	European Hydrogen Backbone
ERW	Electric Resistance Welded
GDN	Gas Distribution Network
GHI	Green Hydrogen International
GGL	(India) Gujarat Gas Limited
GS(M)R	(U.K.) Gas Safety (Management) Regulations
GTI	Gas Technology Institute
GTN	Gas Technology Network
HAZ	Heat-Affected Zone
HFCT	Hydrogen and Fuel Cell Technologies (Office)
HIAD	Hydrogen Incident and Accident Database
HIC	Hydrogen Induced Cracking
HIL	Hydrogen Industry Leaders

H-MAT	Hydrogen Materials Compatibility Consortium
HPCL	Hidustan Petroleum Corporation Ltd.
HSE	(U.K.) Health and Safety Executive
HSL	(HSE's) Health and Safety Laboratory
HTS	Hydrogen Transmission System
HyP SA	Hydrogen Park South Australia
IChemE	(U.K.) Institute of Chemical Engineers
IEA	International Energy Agency
ILI	In-Line Inspection
IM	Integrity Management
IMP	Integrity Management Program
IPA	Intermountain Power Agency
JRC	Joint Research Centre
LEED	Leadership in Energy and Environmental Design
LNG	Liquid Natural Gas
LP	Low Pressure
MIE	Minimum Ignition Energy
MOP	Maximum Operating Pressure
MP	Medium Pressure
NG	Natural Gas
NGN	Northern Gas Networks
NGV	Natural Gas Vehicle
NIC	Network Innovation Competition
NJNG	(U.S.) New Jersey Natural Gas
NREL	National Renewable Energy Laboratory
NTS	(Romania, U.K.) National Transmission System
OCC	Operation Control Center
OIL	(India) Oil India Limited
OTH	(Regensburg, Germany) Ostbayerische Technische Hochschule (University)
P2G or PtG	Power-to-Gas
P2G2P	Power-to-Gas-to-Power
PE	Polyethylene
PEM	Proton Exchange Membrane (Electrolyzer)
PHMSA	Pipeline and Hazardous Materials Safety Administration
PNG	Piped Natural Gas
PNGRB	(India) Petroleum and Natural Gas Regulatory Board
PRCI	Pipeline Research Council International
PTJ	Pipeline Technology Journal
R&D	Research and Development
RL	Remaining Life
RNG	Renewable Natural Gas
RO	Reverse Osmosis
SCADA	Supervisory Control and Data Acquisition
SCC	Stress Corrosion Cracking
SMR	Steam Methane Reforming
SMYS	Specified Minimum Yield Strength

S/N	Stress versus Cycle (Curve)
SNG	Synthetic Natural Gas
SoCalGas	Southern California Gas
SOTA	State of the Art
SP Group	Singapore Power Group
TAP	(This project's) Technical Advisory Panel
TAP	Trans Adriatic Pipeline
TSO	Transmission System Operator
UCI	University of California, Irvine
UGS	Underground Gas Storage
U.K.	United Kingdom
U/S	Upstream
WSHH	(Australia) Western Sydney Hydrogen Hub
WT	Wall Thickness

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List of Variables

da/dN	Crack Growth Rate
dJ/da	Tearing Resistance
J_{Ic}	Fracture Toughness
K	Stress Intensity Factor
K_{max}	Maximum stress intensity factor
K_{min}	Minimum stress intensity factor
ΔK	Stress Intensity Factor Range
N	Number of (Fatigue) Cycles
R-ratio	Loading Ratio
S	Stress

Gases/Chemicals

Ar	Argon
CH_4	Methane
C_2H_6	Ethane
C_3H_8	Propane
C_4H_{10}	Butane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
H_2	Hydrogen
HCl	Hydrogen Chloride
HF	Hydrogen Fluoride
H_2O	Water
H_2S	Hydrogen Sulfide
N_2	Nitrogen
NH_3	Ammonia
O_2	Oxygen
SO_2	Sulfur Dioxide

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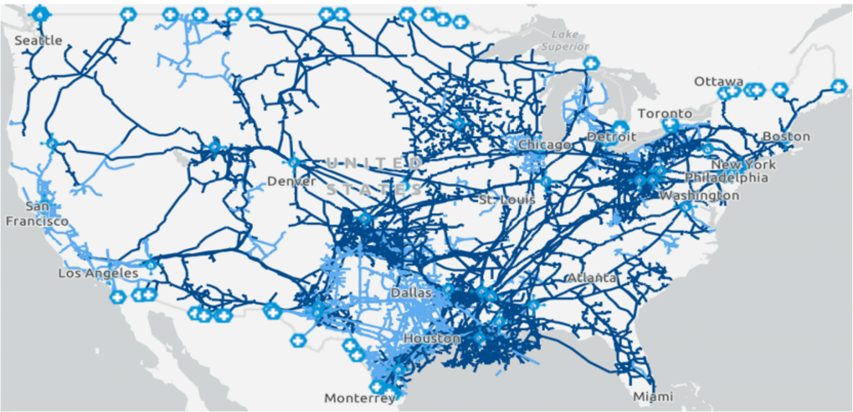
1 INTRODUCTION

This Task 5 report was prepared by Kiefner and Associates, Inc. (Kiefner) as part of the research project titled “Investigate Damage Mechanisms for Hydrogen (H_2) and Hydrogen/Natural Gas Blends to Determine Inspection Intervals for In-Line Inspection (ILI) Tools” for the U.S. Department of Transportation (DOT) Pipeline and Hazardous Materials Safety Administration (PHMSA), under Contract 693JK32310011POTA.

Research[1] under this contract showed that H_2 gas concentrations ranging between 1 and 20% are most proposed for blending, and such concentrations have been used in pilot projects worldwide. However, the pipeline industry is interested in higher concentrations as well. The U.S. natural gas (NG) pipeline network is a highly integrated network that moves NG throughout the country. The pipeline network has approximately 3 million miles (4.8 million km) of mainline and other pipelines that link NG production areas and storage facilities with consumers. Figure 1 shows a map of the NG pipeline networks in the U.S.[2].



eia Source: U.S. Energy Information Administration, U.S. Energy Atlas, January 29, 2024
Note: Light-blue lines are intrastate pipelines, dark-blue lines are interstate pipelines, and + are border crossings.

Figure 1. Map of Continental U.S. Interstate and Intrastate NG Pipelines and Border Crossings[2]

From 2019 to 2024, the U.S. mileage of non-blended (100%) H_2 transmission pipelines[3,4] has increased by 3.6% from approximately 1,522 miles (2,449 km) to 1,578 miles (2,539 km); more than 94% of that mileage is in Texas and Louisiana. Some details of the existing U.S. H_2 pipelines, organized by pipe diameter, vintage, class[1] location, operator, and state, are provided

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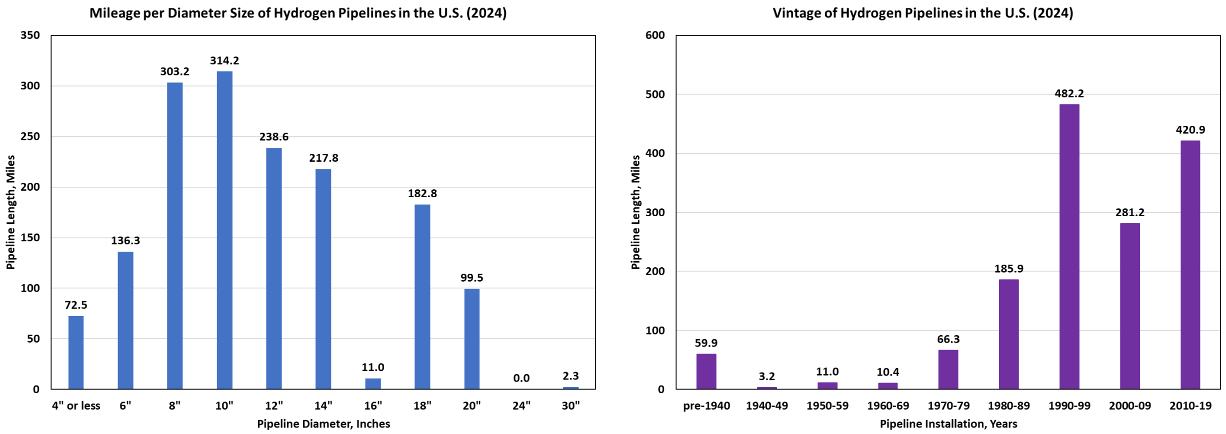
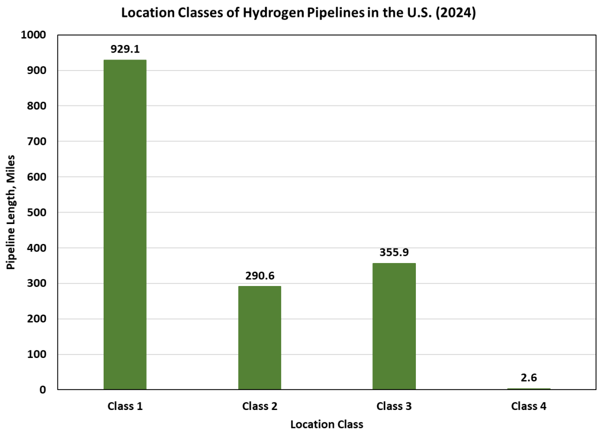
[1] 49 CFR 195.2(b) classifies pipeline locations. A Class 1 location is (i) an offshore area, or (ii) has 10 or fewer buildings intended for human occupancy. A Class 2 location has more than 10 but fewer than 46 buildings intended for human occupancy. A Class 3 location (i) has 46 or more buildings intended for human occupancy; or (ii) the pipeline lies within 100 yards of either a building or a small, well-defined outside area that is occupied by 20 or more persons on at least 5 days a week for 10 weeks in any 12-month period. A Class 4 location is where buildings with four or more stories above ground are prevalent.

in Figure 2. Other countries have more miles of pure H_2 and H_2-blended pipelines. This task analyzed integrity management (IM) experiences from those systems.





Operator	Count	Miles	Percent
#1	5 pipelines	589.6	37.4%
#2	8 pipelines	444.3	28.1%
#3	2 pipelines	367.9	23.3%
30 others	30 pipelines	176.5	11.2%
TOTAL	**45**	**1,578.3**	

State	Miles	Percent
AL	31.0	2.0%
CA	26.4	1.7%
IN	12.0	0.8%
KS	0.4	0.0%
LA	490.7	31.1%
NY	1.0	0.1%
OH	9.2	0.6%
OK	1.5	0.1%
TX	996.7	63.2%
UT	6.4	0.4%
WA	3.0	0.2%
TOTAL	**1,578.2**	

Figure 2. Summary Data of H_2 Pipelines in the U.S.; Source: U.S. DOT-PHMSA Annual Gas Transmission Operator Records (2024)[3,4]

H_2 blending is a complex challenge involving social, economic, and technical considerations. Various research organizations, industry organizations, commercial entities, and communities have contributed to the knowledge developed to date. However, each project has its particular focus and objectives, and combined research is not readily available.

Many aspects are unknown, specifically concerning the interactions between the gaseous H_2 environment, other high-concentration gases in the mix, intentional or unintentional low-concentration constituents, material/gas interface effects, and the long-term structural integrity performance of the transportation infrastructure (pipelines). The associated facilities for H_2 production, storage, treatment, and end use also play a role because the chemistry of the gas and the physics of the construction materials carry through along the supply chain.

Fortunately, prospects for H_2 blending look promising, as evidenced by successful pilot projects and the long-time successful use of "towngas" in different locations worldwide, including Hawai'i, Singapore, and Hong Kong. Towngas is a synthetic fuel gas that is made from naphtha and that contains both methane (CH_4) and H_2 in high concentrations.

This report discusses some aspects associated with H_2 blending into NG, describes the overall status of knowledge, presents a vision for the future, and indicates the need for continued research and development (R&D).

2 BACKGROUND

The H21 Leeds City Gate project report[5] provides some history of H_2 pipelines, from using towngas, which contained approximately 50% of H_2 in the 1800s and early 1900s. These towngas pipelines, made of cast iron, wrought iron, and lead, have largely been replaced or repurposed over time. At present, transmission pipelines with 100% H_2 connect production and demand points in Leeds. Gas pipelines today are constructed of modern materials like steel and polyethylene (PE). The technology is well-established and proven.

The Rhine-Ruhr H_2 pipeline was the first H_2 transmission pipeline. Constructed in 1938, the initial pipeline was 149 miles (240 km) long. The length has been extended over its operational history[6,7]. The pipeline is now 373 miles (600 km) long and still operates today. This pipeline has a diameter of 12 inches (305 mm), a wall thickness of 0.250 to 0.500 inches (6.4 to 12.7 mm), and is made of steel with a yield strength of 65 ksi (450 MPa). The pipeline connects key industrial sites and H_2 production facilities across the Rhine (river) and Ruhr (river) areas. It is part of the European effort to develop an H_2 economy in the region. The report states that as of 2004, there were 900 miles (1,450 km) of H_2 pipelines in the U.S. and 930 miles (1,500 km) in Europe.

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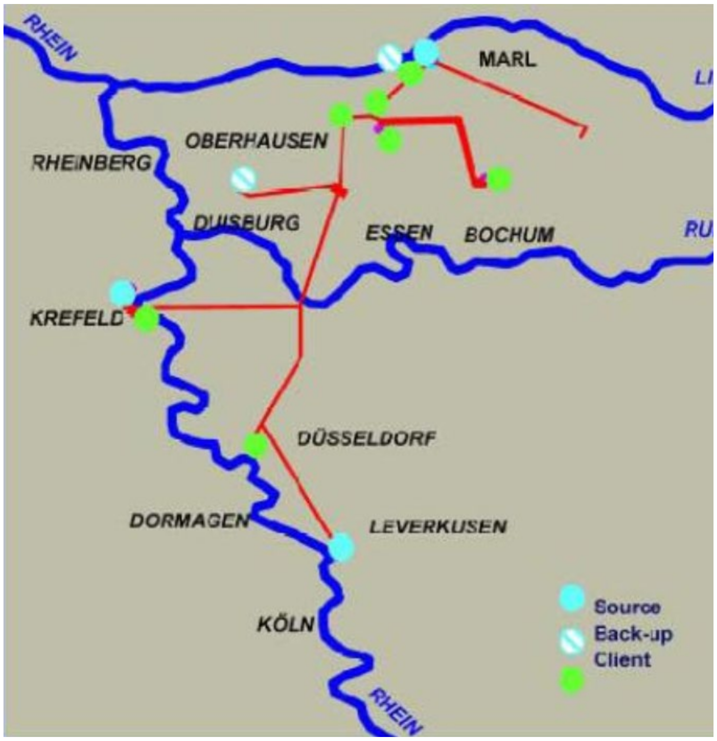

Figure 3. Hydrogen Pipeline System in the Rhine-Ruhr Area[7]

In applications for blending H_2 into NG, a wide range of H_2 contents is considered globally, typically 1 to 20%. The Task 1 literature review[1] for this work showed that interest in the effects of hydrogen on pipeline integrity has increased significantly since 2018 (see Figure 4a) and the interest in H_2/NG blending has also increased since 2019 (see Figure 4b). However, several decades prior, research into the effects of H_2 and H_2 blending had already been conducted.

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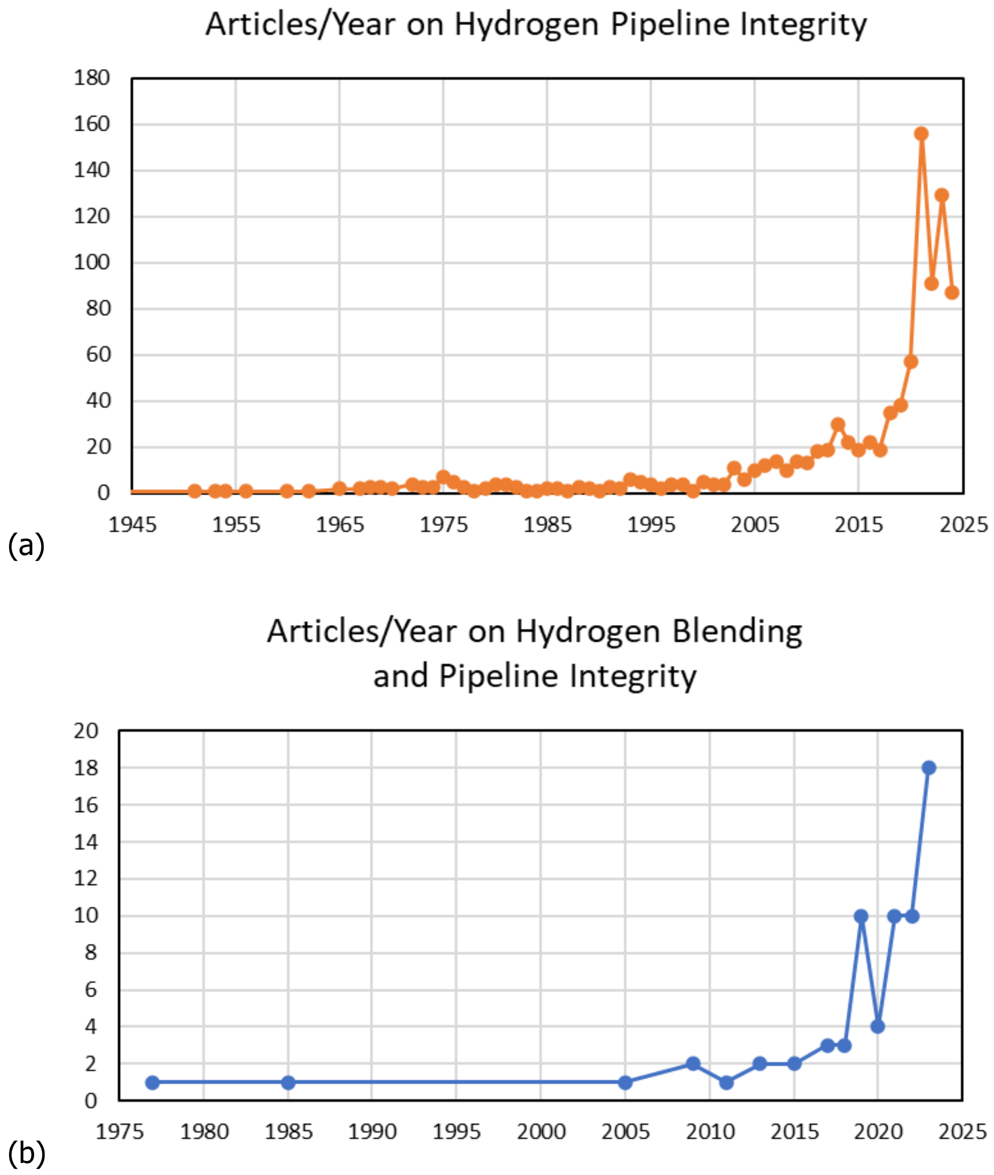

Figure 4. Annual Articles Related to (a) Hydrogen Pipeline Integrity, and (b) Hydrogen Blending and Pipeline Integrity

2.1 European H_2 Backbone

Founded in July 2020, the European Hydrogen Backbone (EH2B) initiative is a group of European energy infrastructure operators covering 25 EU Member states, including the United Kingdom (U.K.), Norway, and Switzerland[8]. With the vision of a pan-European H_2 transport infrastructure, the EH2B has published several flagship maps. An interactive H_2 infrastructure map is given on the following website: https://www.h2inframap.eu/#introduction[9].

The map shows conversion and new infrastructure projects for H_2 production and demand locations, storage sites, transmission and distribution pipelines, 100% H_2, and blended H_2/NG.

Unfortunately, the maps do not include essential information related to integrity management, such as pipe diameter, wall thickness, maximum operating pressure, or steel grade. An inquiry was conducted with the Hydrogen Infrastructure Map team. The team explained that the (mapping) project promoters limit the use of data solely for the creation and display of the map. Therefore, they cannot share the underlying data or a list of projects used to generate the map.

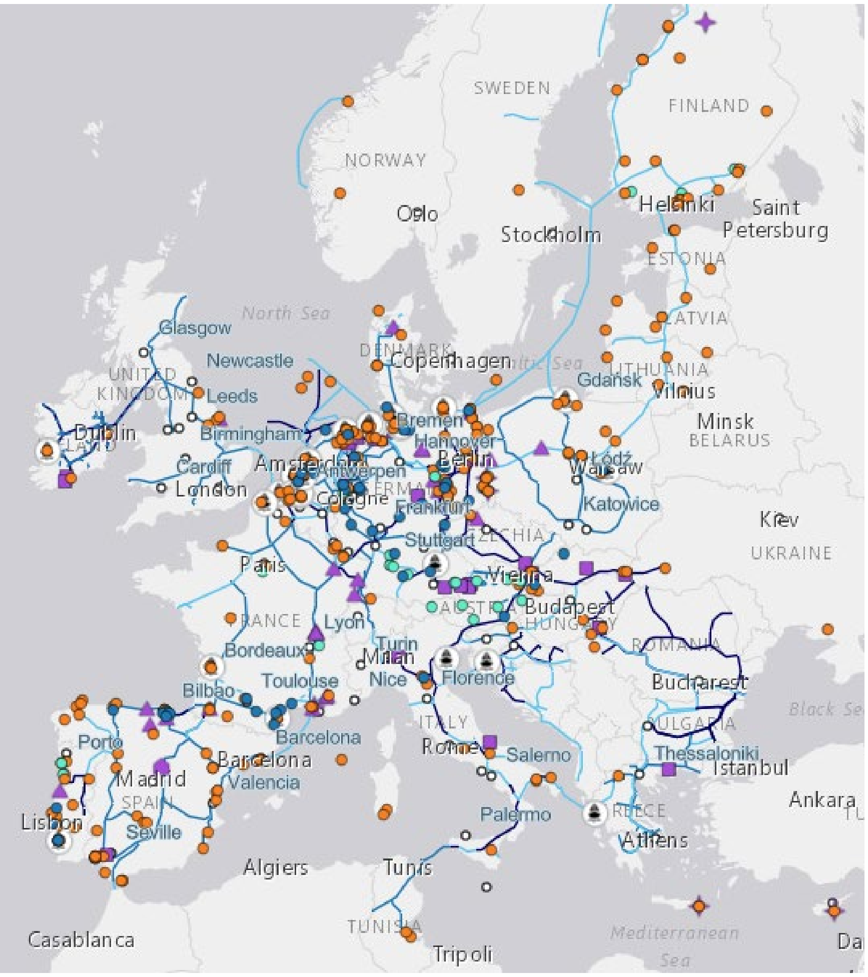

Figure 5. Screen Capture of Hydrogen Infrastructure Map[9]

2.2 NG Quality

NG is a natural fuel product that mostly consists of CH_4. It also contains small amounts of heavier hydrocarbons, such as ethane (C_2H_6), propane (C_3H_8), and butane (C_4H_{10}). It can contain other constituents, such as hydrogen sulfide (H_2S), water, and oxygen (O_2) at lower concentrations. H_2 differs from methane in some important respects. H_2 has a wider (4-74% in air) flammability range than methane (4.4-15%) and can ignite with a smaller minimum ignition energy (MIE) (0.017 mJ) than methane (0.28 mJ). H_2 molecules are smaller than CH_4 molecules, making H_2 more prone to small leaks. H_2 leaks are difficult to detect due to their colorless and odorless nature, requiring specialized sensors. When blending H_2 into other gases, an odorant addition may be needed to increase the probability of leak detection.

NG compositions will vary by source and industrial treatment. Different sources include fossil NG extracted from gas/oil wells, renewable natural gas (RNG) obtained as "biogas" from the anaerobic digestion of biological waste, "landfill gas" naturally released from the decomposition of organic waste in trash, and "sewer gas" produced from wastewater treatment.

Before introducing NG in a transmission pipeline, it is treated to remove most water (dehydration), carbon dioxide (CO_2), and any other contaminants. Removing non-methane organic compounds during the cleaning and conditioning can reduce odors and possible health risks. However, NG will never be 100% pure CH_4. The remaining low concentrations of different chemical compounds in the gas environment can significantly impact how the steel is affected by H_2. Defect assessment procedures used in integrity management programs (IMPs) must account for this.

Gas quality is important because of the end use of H_2. Pure H_2 with low contaminant concentrations can be used as feedstock for fuel cells, as it does not foul the delicate material surfaces within such equipment. Blended H_2 is more likely to be used as an energy carrier within the NG. The mixture can be used for relatively small-scale combustion purposes in homes, such as heating and cooking, or for large-scale purposes, such as fueling an industrial furnace unit or an electric power generation plant. The latter uses will be less restrictive regarding contaminants in the fuel gas.

The minimum federal safety standards for transporting NG and other gases by pipeline are specified in the U.S. Code of Federal Regulations (CFR) Title 49 Part 192[10]. Paragraph 192.3 defines "gas" as a natural gas, flammable gas, or gas that is toxic or corrosive. Thus, H_2/NG blends and 100% H_2 are within the Code's purview. From a technical/engineering perspective, H_2 is not considered a corrosive gas. However, the degradation of mechanical properties by hydrogen embrittlement is well-documented[11, 12]. Yu et al.[13] recently reviewed hydrogen embrittlement knowledge and challenges.

The present project's Task 2 Final Report[14] discussed identifying integrity threats, as required by CFR Paragraph 192.917, with reference to ASME B31.8S, 2018 edition[15], which is incorporated by reference in CFR 192. Although environmental effects are not mentioned beyond internal corrosion, external corrosion, and stress corrosion cracking (SCC), the possible negative environmental interaction between H_2 gas and structural metals, particularly the embrittlement of carbon steel, is well known. Task 3 of the present project will discuss possible changes to industry Codes and Standards to recognize hydrogen effects as an integrity threat.

2.3 Laboratory Testing Versus Full-Scale Demonstration Projects

To isolate the effect of a specific H_2 concentration in laboratory experiments, an inert gas such as nitrogen (N_2) or Argon (Ar) may be used to balance the gas blend instead of 100% CH_4 or NG. Other gas additions, such as oxygen (O2), carbon monoxide (CO), CO2, or water, can be introduced to test for their possible influence.

Research has shown that partial pressures (concentrations) of the individual constituents and total gas pressure affect the outcome of mechanical tests. Furthermore, pressure fluctuations (pressure cycling) impact material properties such as fatigue crack growth rates in steel. For the same maximum operating pressure (MOP), an incipient crack may initiate sooner, while an established crack may grow faster when the gas pressure frequently drops to lower pressures. To interpret the results, the user should consider that the simulated gas environment is designed to investigate certain aspects of interest and that the (treated) NG environment in a pipeline will differ.

Another aspect to consider in evaluating the IM implications of H_2/NG blends is that laboratory experiments are executed using machined specimens. The specimens' dimensions, stress conditions, and external surfaces differ from those of an actual pipeline. For example, the inside diameter surface of an actual pipeline will be covered with various mill scale and corrosion products. In contrast, laboratory specimens will typically be rust-free (machined “fresh”), and laboratory test chambers will be made of non-corrosive metals and likely be cleaned between tests. That way, the test environment is most accurately known.

Full-scale pilot projects using blended gases provide a more realistic representation of an actual pipeline system. Pilot projects typically involve a small system, a limited number of users, and an experience-based evaluation of the exposed components. It is also possible to implement some in-situ monitoring on pilot systems. A challenge associated with pilot projects is their relatively short duration (months to years) compared to the life of a pipeline (decades). Structural integrity effects of components will show as cumulative performance rather than instantaneously measured responses that could be observed in a laboratory setting.

It is recommended that the performance of pipelines with H_2/NG blends be studied using a combination of laboratory experimentation on machined specimens and carefully planned and monitored pilot projects. Based on the results, extrapolations can be made to manage pipeline integrity, including setting the time between inspections.

2.4 U.S. - HyBlend^{TM} Research Project (2020 - Present)

An ongoing research effort in the U.S. is the HyBlend^{TM} project[16,17,18] to address technical barriers to blending H_2 in NG pipelines. The project is led by the National Renewable Energy Laboratory (NREL), conducted by a multi-party consortium of national laboratories and more than 20 industrial partners, and co-funded by the U.S. Department of Energy (DOE). The key objectives of HyBlend^{TM} are to (1) develop an understanding of how H_2 impacts pipes and pipeline components, and (2) assess a pipeline’s capability of H_2 blending and benefit on a case-independent basis.

The HyBlend^{TM} project is organized into three research tasks: H_2 compatibility of piping and pipelines, life-cycle analysis, and techno-economic analysis. The project involves laboratory-scale testing only, and no pilot projects are conducted. The HyBlend^{TM} effort leverages the work of the H-MAT project, which is described next.

Some of the findings from the HyBlend^{TM} project are included in later sections of this report.

2.5 U.S. – H-MAT Research Project (2018 - Present)

DOE's Hydrogen and Fuel Cell Technologies Office (HFCT) Hydrogen Materials Compatibility Consortium (H-MAT)[19] was launched in 2018 in collaboration with over 40 partners in the industry and academia. H-MAT focuses on understanding the effects of H_2 on the performance of polymers and metals used in H_2 infrastructure and storage.

Applications being studied include H_2 blending in NG pipelines, H_2 storage vessels for fueling stations and vehicles, H_2 dispensing components (e.g., hoses, seals, nozzles), materials discovery, and accelerated test methods in H_2. Research activities include high-pressure testing of samples in H_2, multi-scale modeling of hydrogen effects, and microstructural engineering of materials to enhance resistance to hydrogen effects.

R&D on materials compatibility with H_2 at varying pressures, mechanical loads, and temperatures can enable components to be designed at a lower cost. Research outcomes of H-MAT projects will inform industry stakeholders and the Codes & Standards community in the design and operation of H_2 technologies.

Some of the findings from the H-MAT project are included in later sections of this report.

3 OBJECTIVE

The objective of this Task 5 review was to describe how different H_2/NG blends affect pipeline IM intervals.

4 SCOPE OF WORK

The scope of this task included a review of:

- Global experience gained from pilot projects with blended H_2 in pipelines.
- Effects of different H_2 gas percentages, with a focus on:
    - Various types of mechanical integrity threats; and
    - Engineering critical assessment (ECA) procedures to assess the remaining life (RL).
- The reinspection intervals that result from those evaluations:

    - Effects of other constituents in the H_2/NG gas blend; and
    - Unintended impurities, which are either avoidable or unavoidable.
- Intentional additions to inhibit the negative effects of hydrogen on material properties.

5 LABORATORY TESTING IN DIFFERENT H_2/NG BLENDS

5.1 Effects of Partial Pressure of H_2 Gas

In laboratory settings, tests are often designed for screening purposes. Researchers study the effects of certain parameters that can be varied between tests. In the examples presented next, the tests were used to evaluate the potential effect of hydrogen exposure on the mechanical properties of the steels. They were conducted on machined specimens with or without cracks in idealized gas environments, and not on actual defects in full-size pipelines under actual H_2/NG gas blend conditions. Thus, the obtained results should be viewed in this light and not strictly as indicators of the susceptibility to hydrogen embrittlement.

The main problem associated with tests on machined specimens in laboratory environments is the unknown concentration of hydrogen atoms inside the steels, especially at the crack tip during testing. As a result, the obtained results are not necessarily related to the hydrogen effect. If the hydrogen entry and its concentration are not under controllable conditions, the tests would not be appropriate for hydrogen embrittlement testing. In an extreme case, it is possible that no H-atoms enter the steel during testing.

The key to understanding whether the H_2 gas exposure would cause HE in the material is to determine the entry of H-atoms into the steels. The exposure environment is H_2 gas, while the occurrence of HE depends on H-atoms. In gaseous environments, a method that can quantitatively measure the H-atom entry into the steels is essential to provide deterministic answers to the question.

In Task 7 of this project, which will be executed later this year and next year, more research will be conducted to validate observations of hydrogen effects versus non-hydrogen effects.

5.1.1 University of Grenoble Research – Effects of H_2 Concentration in Blended Gas

Briottet and Ez-Zaki[20] conducted toughness measurements in terms of crack tip opening displacement (CTOD) on an American Petroleum Institute (API) 5L[21] Grade X70 steel in different H_2/N_2 gas mixtures at a total pressure of 1,232 psig (85 bar). They found that even a low 1% H_2 content in N_2 induced a significant decrease in the material toughness (a decrease in the force required to achieve a certain CTOD). Further decreases in CTOD were observed for 10% H_2 and pure H_2 (see Figure 6).

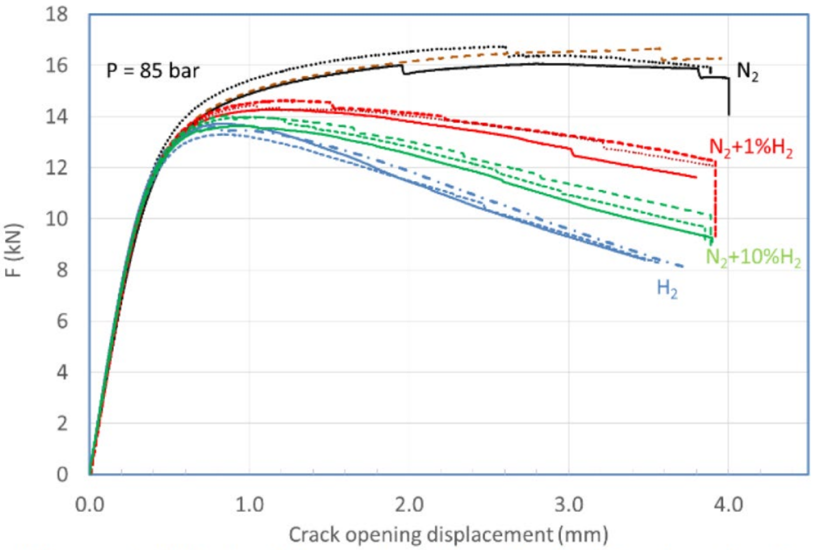

Figure 2: Effect of H_2 content in a N_2+H_2 blend on load-crack opening curves

Figure 6. "Figure 2" from Briottet and Ez-Zaki[20], Showing Required Force as Function of Crack Opening Displacement in Pure Nitrogen, 1% H_2/N_2 Blend, 10% H_2/N_2 Blend, and Pure H_2 Conducted on an API X70 Pipeline Steel at a Total Pressure of 1,232 psig (85 bar)

5.1.2 Sandia Research

Ronevich and San Marchi[17,22] reported test results of fatigue crack growth rate (CGR) and fracture resistance of a modern API 5L X52 pipeline steel in H_2/N_2 blended gas environments at 500 psig (3.4 MPa) and 3,000 psig (21 MPa). By using (high-purity) laboratory-grade gases, they eliminated the possible effects of impurities, such as O_2 or CO. The fatigue CGR increased with increasing partial pressure of H_2 (see Figure 7). The CGRs measured on electric resistance welded (ERW) long-seam metal were higher than CGRs measured on base metal, and as expected, both were higher than the CGRs in air (see Figure 8).

The fracture resistance in H_2-blended N_2 was lower than that in air. The fracture resistance decreased with increased partial pressure of H_2 (see Figure 9). Similarly, the fracture resistance in pure H_2 decreased with increased pressure (see Figure 10).

Overall, Ronevich and San Marchi concluded that the basic trends on fatigue and fracture due to testing in the mixed gas environment followed the trends established in pure H_2 at high pressure. However, at a higher driving force (i.e., high stress intensity factor range (ΔK)), the fatigue CGR was independent of pressure and an order of magnitude greater than in air, even for H_2 partial pressure as low as 14.5 psig (0.1 MPa.)

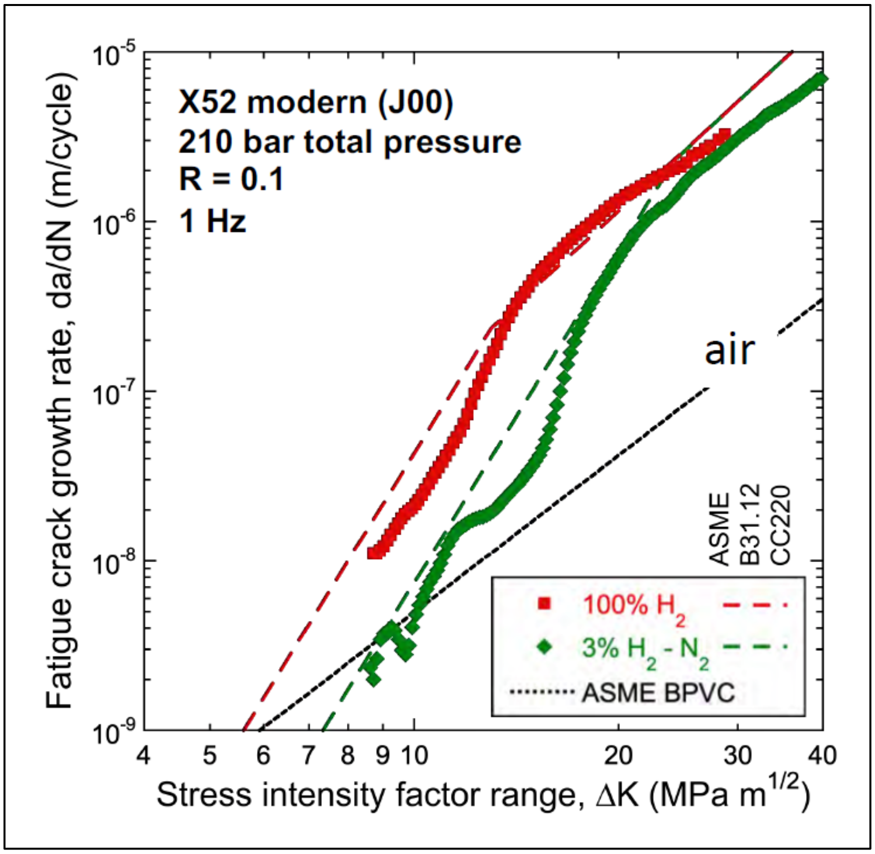

Figure 7. Sandia National Laboratories Data[17] for Fatigue Crack Growth Rate Tests in 3% H_2/N_2 Blended Gas and Pure Hydrogen, Conducted on a Modern X52 Pipeline Steel at a Total Pressure of 3,000 psig (210 bar), Frequency of 1 Hz and R-Ratio = 0.1

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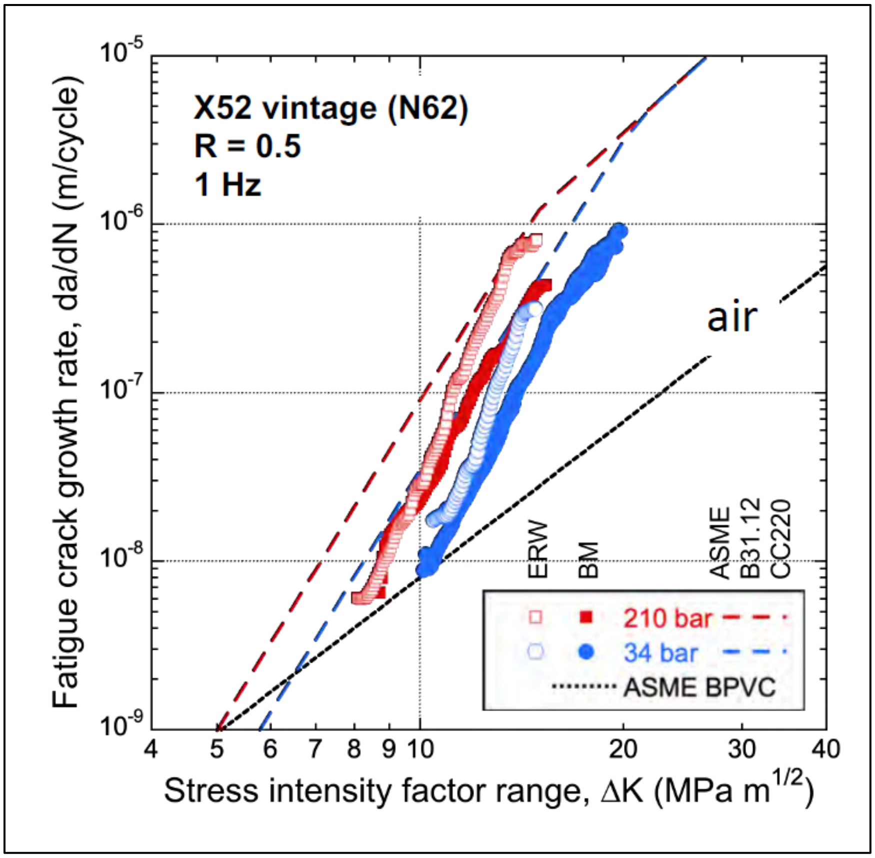

Figure 8. Sandia National Laboratories Data[17] for Fatigue Crack Growth Rate Tests in 3% H_2/N_2 Blended Gas and Pure Hydrogen, Conducted on a Vintage X52 Pipeline Steel Base Metal (BM) and Electric Resistance Welded (ERW) Seam Weld Metal at Pressures of 500 psig (3.4 MPa) and 3,000 psig (21 MPa), Frequency of 1 Hz and R-Ratio = 0.5

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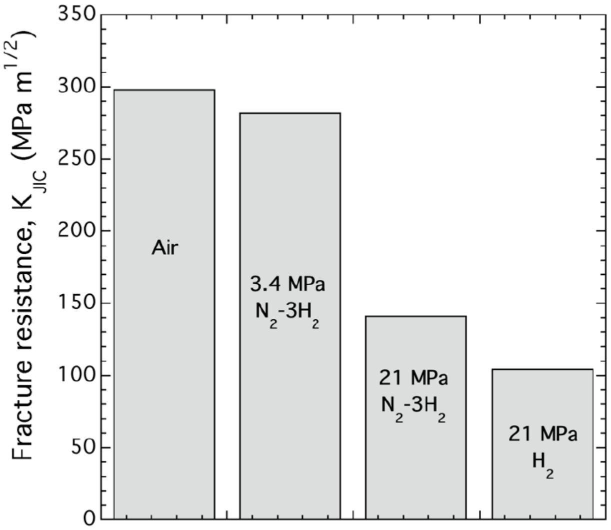

FIGURE 2: FRACTURE RESISTANCE (K_{JIC}) OF X52 PIPELINE STEELS IN GASEOUS HYDROGEN ENVIRONMENTS.

Figure 9. “Figure 2” from Ronevich and San Marchi[22] for Fracture Resistance Tests in Air, 3% H_2/N_2 Blended Gas, and Pure Hydrogen, Conducted on X52 Pipeline Steels (Different Materials) at Total Pressures of 500 psig (3.4 MPa) and 3,000 psig (21 MPa)

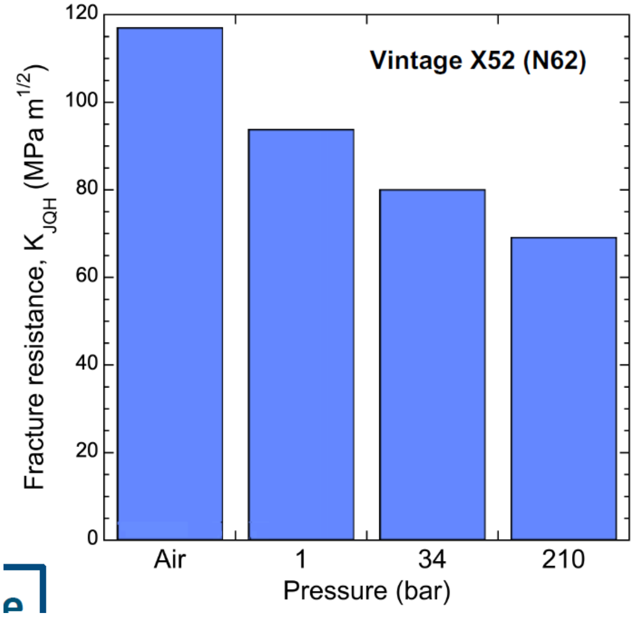

Figure 10. Sandia National Laboratories Data[17] for Fracture Resistance Tests in Air, and Pure H_2 at 14.5 psig (0.1 MPa), 500 psig (3.4 MPa) and 3,000 psig (21 MPa) Conducted on a Vintage X52 Pipeline Steel

5.2 Effects of Contaminants in H_2 Gas

5.2.1 1980s Battelle Research

From 1982 to 1988, Cialone and Holbrook[23,24,25,26,27] published results of testing API 5L grade X42, X52, X60, and X70 line pipe steels in synthetic natural gas (SNG) H_2-rich mixtures, compared with Ar and CH_4. The test conditions are summarized in Table 1, where "M" signifies 100% CH_4 gas, "MH" signifies a CH_4/H_2 blend, "MHC" signifies a $CH_4/H_2/CO_2$ blend, and "MHCC" signifies a $CH_4/H_2/CO_2/CO$ blend. The latter mix was also saturated with water-vapor. All tests were conducted with a total gas pressure of 1,000 psig.

They found that under cyclic loading, hydrogen-accelerated fatigue-crack growth occurred, depending on frequency, stress ratio(2) (R-ratio), stress intensity range(3), and the composition of the gas mixture in the environment.

Table 1. "Table 2" from Holbrook and Cialone[25]

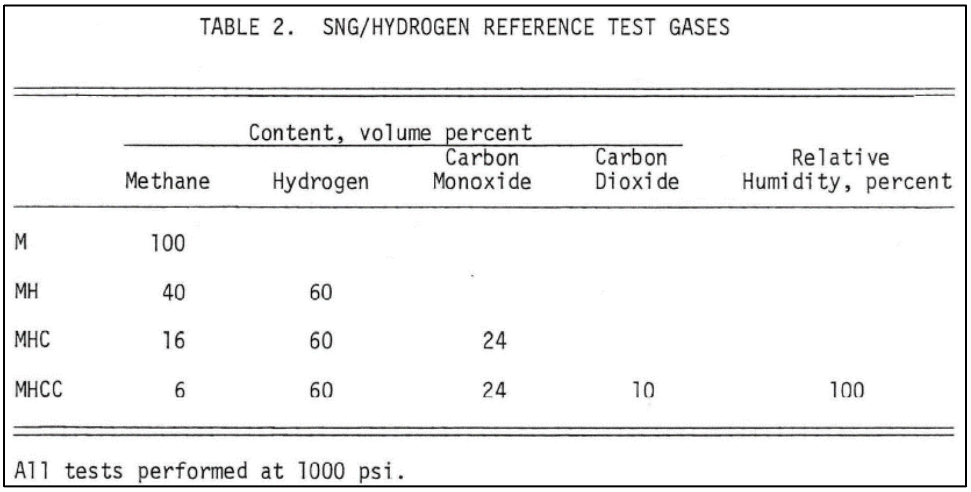

TABLE 2. SNG/HYDROGEN REFERENCE TEST GASES

	Content, volume percent				
	Methane	Hydrogen	Carbon Monoxide	Carbon Dioxide	Relative Humidity, percent
M	100				
MH	40	60			
MHC	16	60	24		
MHCC	6	60	24	10	100

All tests performed at 1000 psi.

5.2.1.1 Effects of H_2 Blending on Fatigue Cycles to Failure

Fatigue stress-cycle (S/N) curves showed that H_2 in the gas mixture shortens fatigue life compared to testing in Ar, but that CO, CO_2, and even CH_4 can inhibit the shortening of the fatigue life (see Figure 11).

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[2] The stress ratio, commonly referred to as the loading ratio or R-ratio, is defined as the maximum load divided by the minimum load.

[3] The stress intensity range is defined as the maximum stress intensity factor (K_{max}) divided by the minimum stress intensity factor (K_{min}) of a stress cycle.

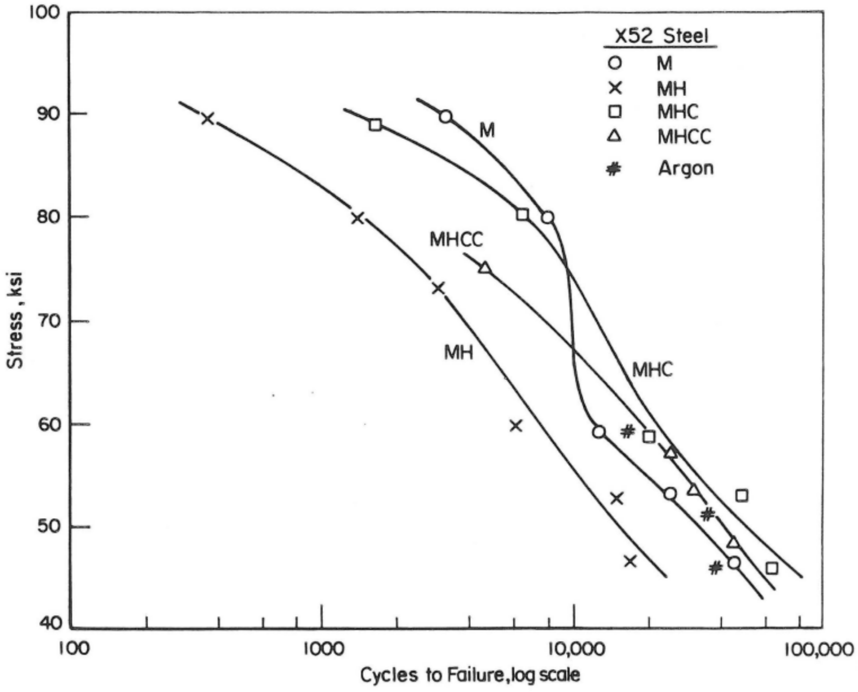

FIGURE 14. FATIGUE LIFE FOR X52 STEEL IN FOUR SNG/HYDROGEN GAS MIXTURES LISTED IN TABLE 2, AS WELL AS THREE TESTS IN PURE ARGON AT 1000 psi (DENOTED BY #)

Figure 11. "Figure 14" from Holbrook and Cialone[25] for Gas Mixtures M = 100% CH_4, MH = CH_4/H_2, MHC = $CH_4/H_2/CO$, MHCC = $CH_4/H_2/CO/CO_2$. This Low Cycle Fatigue Testing Was Performed Using Notched Specimens, a Sinusoidal Load Waveform, a Test Frequency of 1 Hz, and an R-Value of Less Than 0.1.

Holbrook and Cialone found that a steel's behavior in a CO-inhibited gas mixture (MHC) was often better than that in pure CH_4. They offered possible explanations for these observations, such as CH_4 not representing a truly inert environment or that a reaction between H_2 and CO occurred on, and possibly was catalyzed by, the clean steel surface exposed during the fracture process.

Holbrook and Cialone rationalized the behavior shown in Figure 11, in part by considering that the reaction

$$CO + 3H_2 = CH_4 + H_2O \qquad \text{Equation 1}$$

may be promoted by clean steel that is produced by crack growth and/or slip steps on a surface. This reaction would consume hydrogen on the surface and produce water, a potent inhibitor of H_2 degradation. A clean (not oxidized) steel surface is a potential catalyst for the reaction.

Added support for the mechanism suggested by $CO + 3H_2 = CH_4 + H_2O$ was obtained by performing fatigue tests on grade X60 specimens at various test frequencies and for a stress amplitude where inhibition was incomplete. The fatigue S/N curves are shown in Figure 12. If the proposed inhibition reaction, $CO + 3H_2 = CH_4 + H_2O$, proceeds at a finite rate as is likely for a chemical reaction requiring catalysis, inhibition by CO should improve at lower test frequencies, as shown in Figure 12.

In 2022 and 2024, Chinese and Canadian researchers published papers[28,29], contradicting Holbrook and Cialone's explanation of the dissociative adsorption of H_2 and CH_4 molecules and the inhibiting effect of CO. Those researchers argue that the proposed reaction in Equation 1 barely occurs at normal temperatures, and that any oxygen-containing gas molecules such as O_2, CO and H_2O vapor can competitively adsorb on steel surface, mitigating the adsorption of H_2 gas molecules. Consequently, the hydrogen dissociation on steel is inhibited.

If, as proposed by Holbrook and Cialone, the reaction $CO + 3H_2 = CH_4 + H_2O$ does indeed apply to the situation of inhibition in MHC gas mixtures, it also can help to explain the observations shown in Figure 11 with longer fatigue lives at low stresses in MHC than in Ar. In that case, the apparent explanation would be that the water vapor liberated by the reaction, in turn, reacts with the steel surface in a corrosive manner to produce crack-closure effects that reduce the effective stress amplitude in fatigue. Similarly, Figure 12 shows that measured fatigue lives in the MHC gas mix (with CO) exceeded those in the MH gas mix, which did not have CO to provide fatigue CGR inhibition.

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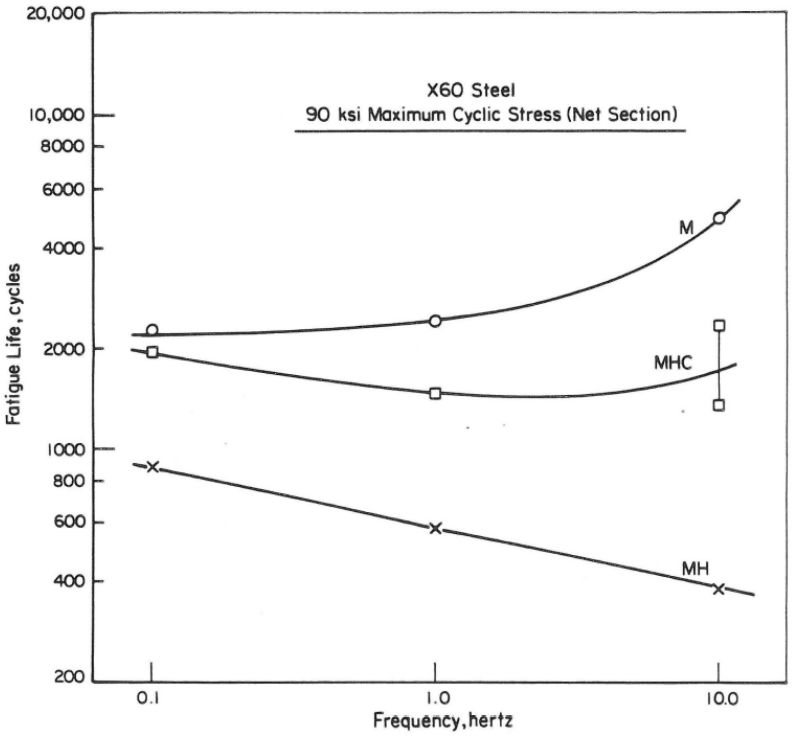

FIGURE 15. FATIGUE LIFE FOR X60 STEEL IN THE THREE ENVIRONMENTS LISTED IN TABLE 2 VERSUS TEST FREQUENCY

Stress amplitude was fixed at 90 ksi for all tests.

Figure 12. "Figure 15" from Holbrook and Cialone[25] for Fatigue Life Tests Conducted at a Stress Amplitude of 90 ksi on X60 Steel for Gas Mixtures M = 100% CH_4, MH = CH_4/H_2, MHC = $CH_4/H_2/CO$, MHCC = $CH_4/H_2/CO/CO_2$. This Low Cycle Fatigue Testing Was Performed Using Notched Specimens, a Sinusoidal Load Waveform, Frequencies of 0.1 Hz, 1 Hz, and 10 Hz, and an R-Value of Less Than 0.1.

5.2.1.2 Effects of Blending on Fracture Toughness

In Cialone and Holbrook's experiments on specimens subjected to static load and exposed to a blend of 40% H_2/60% CH_4, subcritical crack growth occurred in high-hardness steels, API X52 ERW heat affected zones (HAZs), and API X42 pipeline steel heat-treated to simulate local "hard spot" regions. J-integral fracture toughness experiments showed that H_2 reduces the fracture toughness, J_{Ic}, [intersection of J-resistance curve and blunting line(4)], and in steels that undergo subcritical crack growth, H_2 reduces the tearing resistance, dJ/da, [slope of the J-resistance curve] (see Figure 13).

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[4] The blunting line is a mathematically derived line, based on the material's strength properties, which accounts for apparent but artificial crack growth arising from extensive crack-tip blunting.

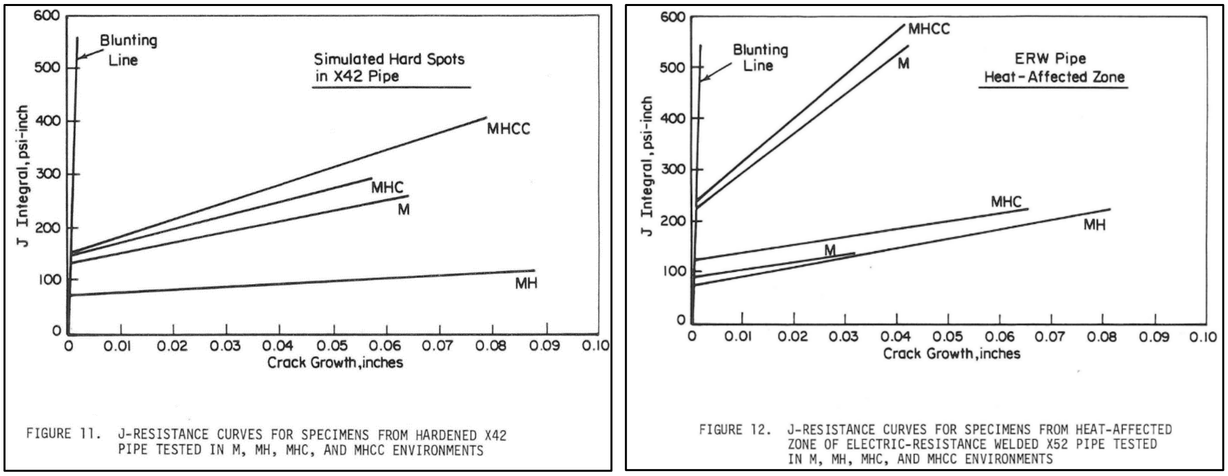

FIGURE 11. J-RESISTANCE CURVES FOR SPECIMENS FROM HARDENED X42 PIPE TESTED IN M, MH, MHC, AND MHCC ENVIRONMENTS

FIGURE 12. J-RESISTANCE CURVES FOR SPECIMENS FROM HEAT-AFFECTED ZONE OF ELECTRIC-RESISTANCE WELDED X52 PIPE TESTED IN M, MH, MHC, AND MHCC ENVIRONMENTS

Figure 13. “Figure 11” and “Figure 12” from Holbrook and Cialone[25] for Gas Mixtures M = 100% CH_4, MH = CH_4/H_2, MHC = $CH_4/H_2/CO$, MHC = $CH_4/H_2/CO/CO_2$

5.2.2 Effects of O_2 in H_2 Blended Gas - University of Grenoble Research

Briottet and Ez-Zaki[20] studied the influence of the O_2 content in 1% H_2/N_2 gas mixtures with 10 ppm (by volume), 50 ppm, 100 ppm O_2, and a total pressure of 1,232 psig (85 bar). They conducted toughness measurements, in terms of CTOD, on an API X70 steel. They did not observe a decrease in the fracture toughness at 10 ppm O_2 but did measure a significant decrease in the curves for 50 ppm and 100 ppm O_2, as compared to pure N_2 (see Figure 14). They concluded that O_2 can mitigate the detrimental effect of H_2 on X70 steel for O_2 concentrations higher than 50 ppm.

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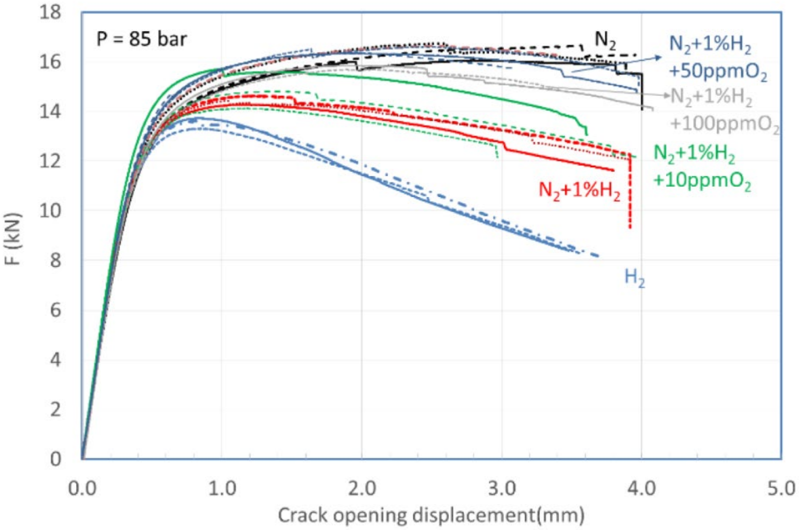

Figure 4: Effect of O$_2$ content in a N$_2$+1%H$_2$ blend on load-crack opening curves

Figure 14. "Figure 4" from Briottet and Ez-Zaki[20] Showing Required Force as a Function of Crack Opening Displacement in Pure N$_2$, 1% H$_2$/N$_2$ Blend with Different O$_2$ Concentrations, and Pure H$_2$, Conducted on an API X70 Line Pipe Steel at a Total Pressure of 1,232 psig (85 bar)

5.2.3 Effects of Blending on Fatigue Crack Growth Rates

Cialone and Holbrook[26,27] measured fatigue CGR curves of ΔK, versus CGR per cycle, da/dN, as provided next. Figure 15, Figure 16, and Figure 17 show pronounced increases in da/dN for tests conducted on grade X42 and X70 steel specimens at 1,000 psig (6.9 MPa) in 100% N$_2$ and 100% H$_2$ gas at load ratios (R-ratio) of 0.1 and 0.8.

Figure 18 shows the dependency of the fatigue CGRs on R-ratio from tests performed on grade X42 steel specimens at ΔK ≈ 10 MPa√m (≈ 1.45 ksi√in.)(5). For tests in N$_2$, the CGR increased with an increasing ratio. For tests in H$_2$, the CGR per cycle was constant for R-ratios of 0.4 or less. For R-ratios above 0.4, the CGR increased with increasing R-ratio.

Figure 19 shows the dependency of the fatigue CGRs on K_{max}, ΔK, and R-ratio for an API 5L X42 steel. The CGR increases with increasing K_{max}, increasing ΔK, and decreasing R-ratio.

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[5] (MPa√m) * 0.145038 = (ksi√in)

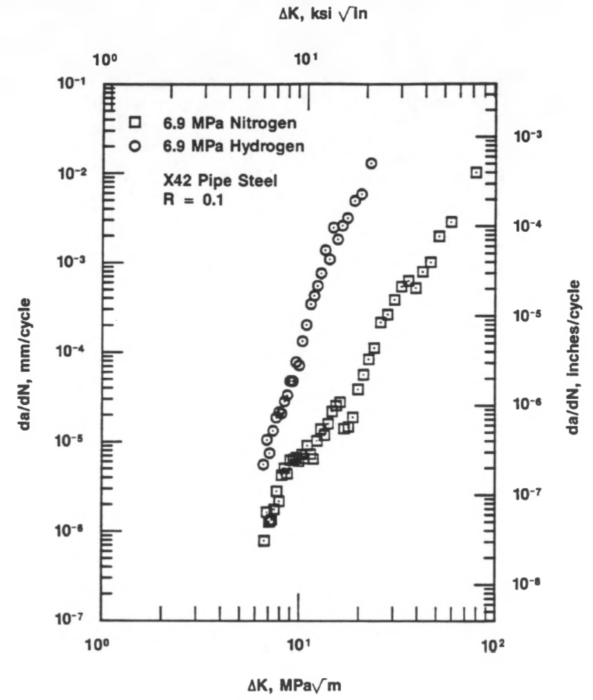

FIGURE 25. FATIGUE-CRACK-GROWTH BEHAVIOR FOR X42 PIPE STEEL IN 6.9 MPa (1000 psi) HYDROGEN AND IN 6.9 MPa (1000 psi) NITROGEN AT A FREQUENCY OF 1 HERTZ (5 HERTZ IN NITROGEN) AND R = 0.1

Figure 15. "Figure 25" from Holbrook and Cialone[26] Fatigue Crack Growth Rates in 1,000 psig (6.9 MPa) N_2 and H_2 for X42 Steel at R=0.1

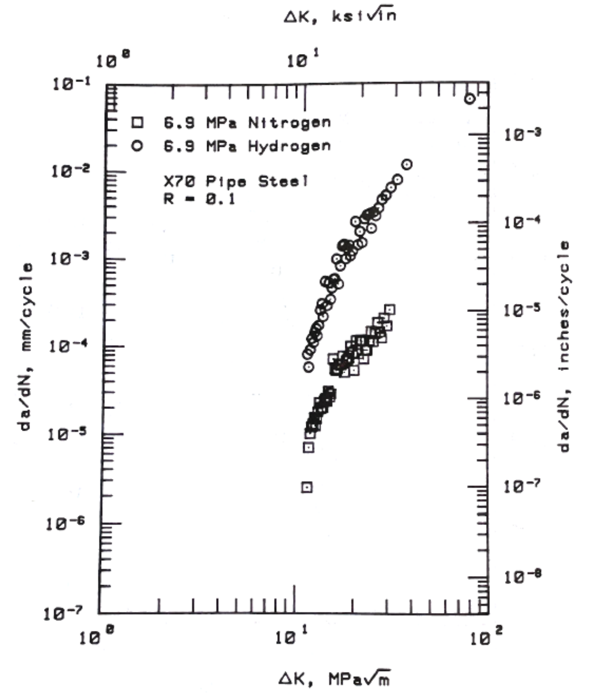

FIG. 2—*Fatigue-crack-growth rates for X70 pipe steel in 6.9-MPa (1000-psi) hydrogen and in 6.9-MPa (1000-psi) nitrogen at R = 0.1.*

Figure 16. "Figure 2" from Holbrook and Cialone[27] Fatigue Crack Growth Rates in 1,000 psig (6.9 MPa) N_2 and H_2 for X70 Steel at R=0.1

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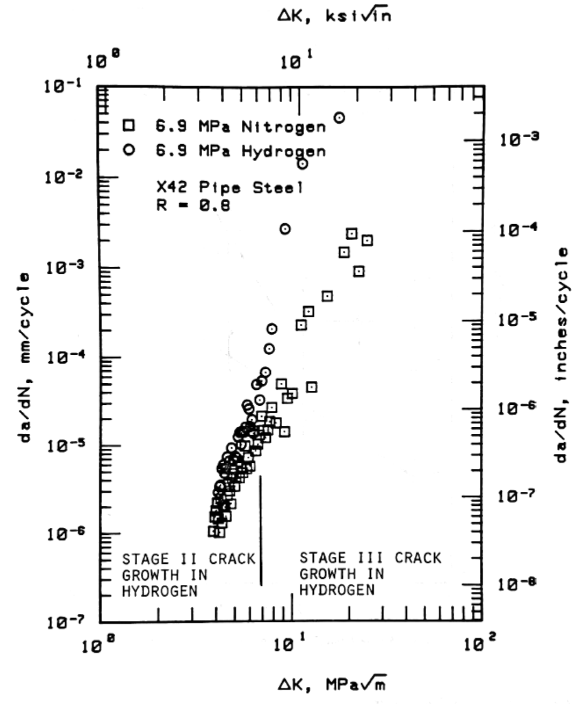

FIG. 3—*Fatigue-crack-growth rates for X42 pipe steel in 6.9-MPa (1000-psi) hydrogen and in 6.9-MPa (1000-psi) nitrogen at* R = *0.8.*

Figure 17. "Figure 3" from Holbrook and Cialone[27] Fatigue Crack Growth Rates in 1,000 psig (6.9 MPa) N_2 and H_2 for X42 Steel at R=0.8

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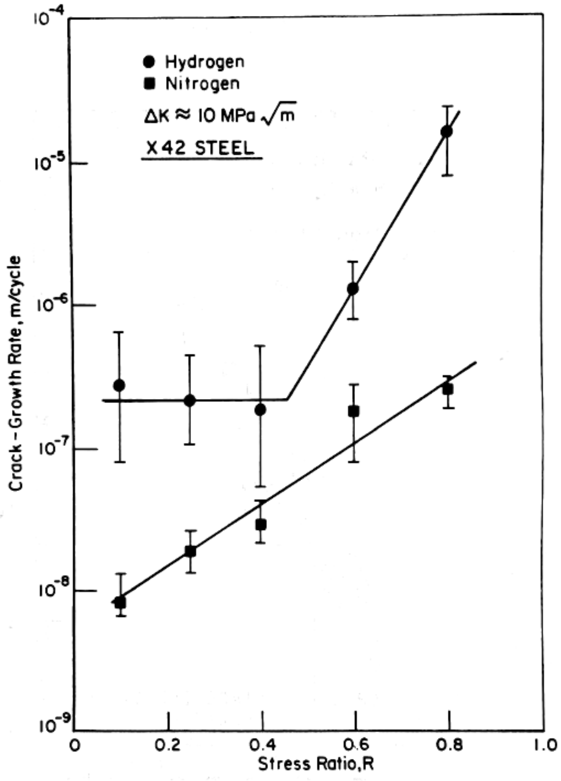

FIG. 4—*Fatigue-crack-growth rate for X42 pipe steel as a function of stress ratio.*

Figure 18. "Figure 4" from Holbrook and Cialone[27] for Fatigue Crack Growth Rate Tests Conducted in 1,000 psig (6.9 MPa) N_2 and H_2 for X42 Steel, Showing the Effect of Different R-Ratios

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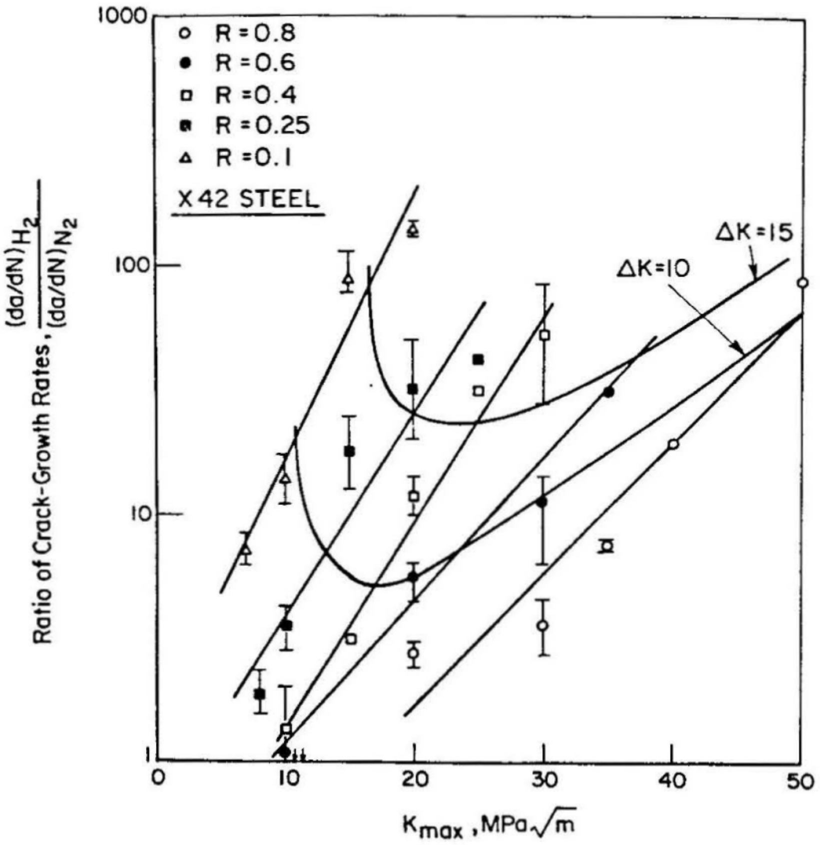


Fig. 5—Influence of K_{max} on fatigue-crack acceleration in hydrogen.

Figure 19. "Figure 5" from Holbrook and Cialone[24] for Fatigue Crack Growth Rate Tests Conducted in 6.9 MPa N_2 and H_2 for X42 Steel, Showing the Effects of Different Stress Intensities (K), Stress Intensity Factor Ranges (ΔK), and Different R-Ratios

5.3 Effects of Contaminants in H_2 Gas

5.3.1 1980s Battelle Research

Using ΔK-da/dN curves, Cialone and Holbrook[27] also showed the reduction or elimination of hydrogen-degradation effects by the presence of certain inhibitor/impurity/contaminant gases, such as O_2, sulfur dioxide (SO_2), or CO. For fatigue tests of a grade X42 steel at an R-ratio of 0.1, in H_2 gas with relatively small additions of other gases, Figure 20, Figure 21, and Figure 22 show the curves for 100 ppm O_2, 2% SO_2, and 2% CO, respectively. With the other gas additions, the crack growth rates reduced compared with 100% H_2 and approached the CGR in 100% N_2.

Figure 23 shows the ΔK-da/dN curve for a test on X42 steel at an R-ratio of 0.8 in H_2 plus 100 ppm O_2, in which the CGR was even lower than that in N_2. Thus, the concentration of the impurity gas and the R-ratio of the test played a role.

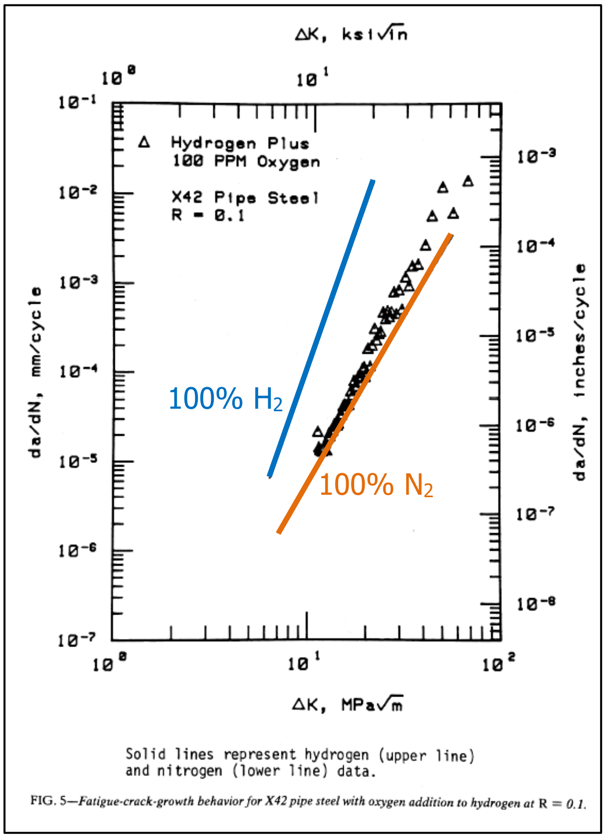


Figure 20. "Figure 5" from Holbrook and Cialone[27] Fatigue Crack Growth Rates in 6.9 MPa H_2 Plus 100 ppm O_2, Compared with Curves for 100% N_2 and 100% H_2 for X42 Steel at R=0.1

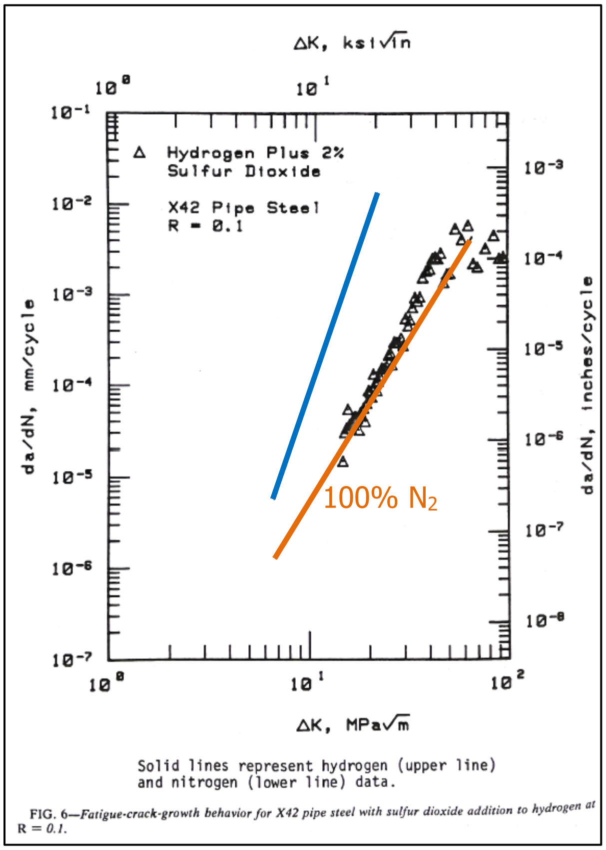
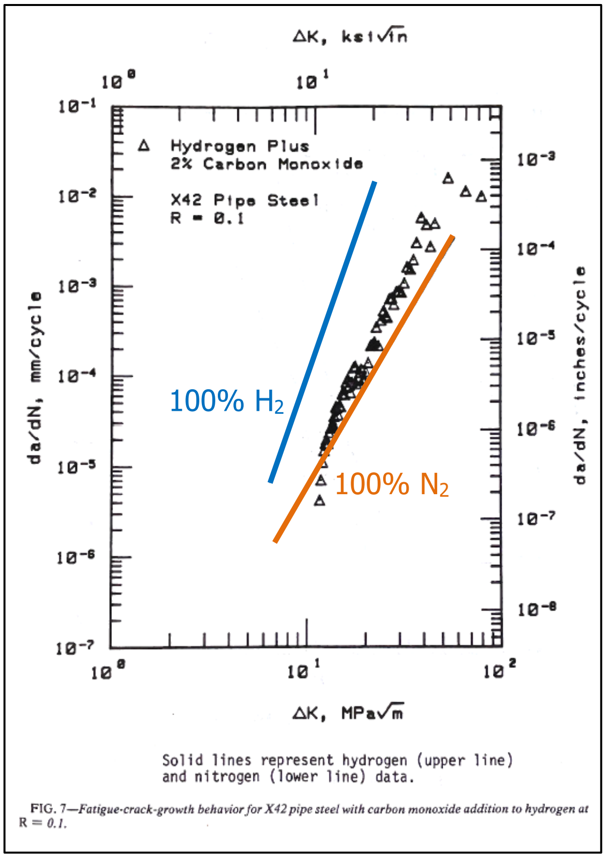
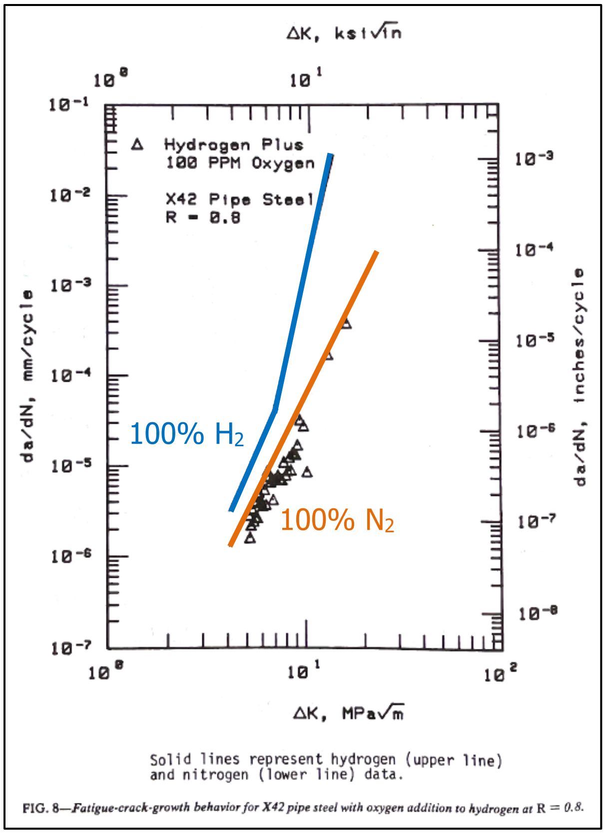


Figure 21. "Figure 6" from Holbrook and Cialone[27] Fatigue Crack Growth Rates in 6.9 MPa H_2 Plus 2% SO_2, Compared with Curves for 100% N_2 and 100% H_2 for X42 Steel at R=0.1



Solid lines represent hydrogen (upper line) and nitrogen (lower line) data.

FIG. 7—*Fatigue-crack-growth behavior for X42 pipe steel with carbon monoxide addition to hydrogen at R = 0.1.*



Solid lines represent hydrogen (upper line) and nitrogen (lower line) data.

FIG. 8—*Fatigue-crack-growth behavior for X42 pipe steel with oxygen addition to hydrogen at R = 0.8.*

Figure 22. "Figure 7" from Holbrook and Cialone[27] Fatigue Crack Growth Rates in 6.9 MPa H_2 Plus 2% CO, Compared with Curves for 100% N_2 and 100% H_2 for X42 Steel at R=0.1

Figure 23. "Figure 8" from Holbrook and Cialone[27] Fatigue Crack Growth Rates in 6.9 MPa H_2 Plus 100 ppm O_2, Compared with Curves for 100% N_2 and 100% H_2 for X42 Steel at R=0.8

6 HISTORY OF H_2 BLENDING

6.1 Introduction to H_2 Blending Pilot Projects

Existing NG storage, transmission, distribution, and end-use infrastructure has evolved over 200 years since early "towngas" systems. Those early systems, which often handled gas compositions greater than 50% H_2, have transitioned into NG-based systems for storing, transporting, and supplying primary CH_4. As Standards allow, small concentrations of other components may also be present in the gas.

6.1.1 SoCalGas H_2 Blending Description (2024)

In March 2024, the Southern California Gas (SoCalGas) utility company provided a general description[30] of H_2 blending into NG, which also describes H_2 blending demonstration projects.

Figure 24 shows an illustration of the typical infrastructure components required for H_2 blending.

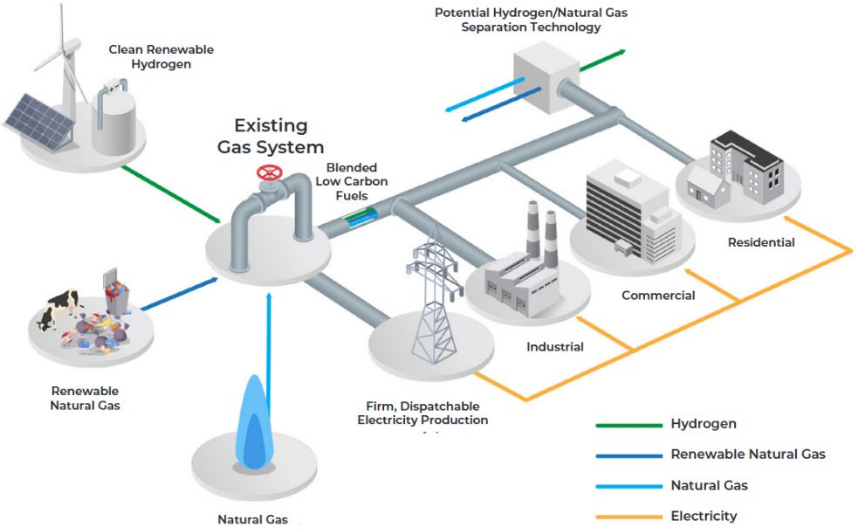


Figure 24. Illustration of Hydrogen Blending Infrastructure[30]

The SoCalGas publication refers to proven and safe H_2 blending experience, with use for decades in European countries like Belgium, Denmark, France, Germany, Italy, and the U.K. (up to 20% H_2 blend) and Canada (up to 5% H_2 blend). There are H_2 blending projects underway in the continental U.S. (up to 5% H_2 blend). Since 1974, Hawai'i Gas has used H_2 in its fuel mix (up to 15% H_2 blend) for homes and businesses. More details of these projects are provided elsewhere in this report.

6.1.2 Riverside/GTI Study (2022)

A July 2022 study[50] commissioned by the State of California and performed by the University of California, Riverside and their subcontractor, Gas Technology Institute (GTI), identified the following possible concerns with H_2 blending into NG:

- Maximum H_2 percentage at which no or minor modifications are needed for NG infrastructure and end-use systems;
- Types of modifications that may be required for higher percentages of H_2;
- Impacts on end-use appliances and safety implications;
- Impacts, including degradation, on the durability of the existing NG pipeline system;
- Impacts on NG pipeline leakage rates;
- Impacts on valves, fittings, materials, and welds due to hydrogen embrittlement;

- Impacts on NG storage facilities; and
- Impacts on pipelines under cathodic protection (CP).

As part of the study, the project team exposed select metals and alloys used in the NG transmission systems to hydrogen through gaseous exposure and electrochemical charging. The exposed metal samples were subjected to tensile strength tests and impact tests to assess material toughness, followed by characterization using several techniques. The results showed that hydrogen-charged steel samples exhibited characteristics of hydrogen-induced embrittlement, which affects the material's strength and toughness.

The study found that, based on many overlapping variable conditions, a systemwide blending injection scenario becomes concerning as H_2 blending approaches 5% by volume. As the percentage of H_2 increases, end-use appliances may require modifications, vintage materials may experience increased susceptibility, and legacy components and procedures may be at increased risk of H_2 effects.

Conclusion for IM: The Riverside/GTI study for pipeline IM is that H_2 blending affects the durability of the existing NG pipeline system, including valves, fittings, materials, and welds, due to hydrogen embrittlement.

6.1.3 PRCI State-of-the-Art Analysis (2020)

In the Riverside/GTI Study (2022), for the maximum H_2 percentage at which no or minor modifications are needed, reference is made to a November 2020 Pipeline Research Council International (PRCI) State of the Art (SOTA), Gap Analysis, and Future Project Roadmap[31]. The PRCI analysis included mapping over 100 projects worldwide and identified over 340 technical resources. Figure 25 visually compares the then-current (2020) knowledge coverage for each key challenge at different H_2 injection and blending levels, as reported by PRCI. The Technical Advisory Panel (TAP) of this present PHMSA project let us know that the figure has since been revised as it was easily misinterpreted as "hydrogen injection/blending is possible at these percentages," while the intention was "level of knowledge/experience available at these percentages."

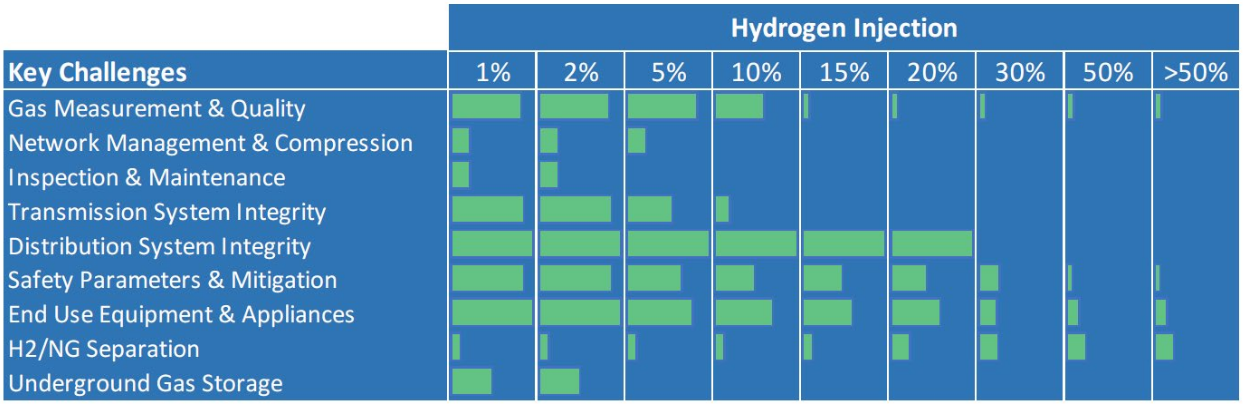


Figure 25. 2020 Knowledge Coverage for Each Key Challenge at Different H_2 Injection and Blending Levels[31]

The following statement was provided in the Riverside/GTI Study (2022)[31]:

> "The body of literature reports that in relatively low H_2 concentration (1-5% by volume), this approach seems to be viable without significantly increasing risk factors in the storage, transmission, and utilization of H_2 blends."

However, as related to integrity management of pipelines carrying H_2/NG blends, the Riverside/GTI recommendations indicated that much is still unknown and more research is needed:

1. Perform case-by-case studies to determine the appropriate blend percentage suitable to mitigate operational risks, public safety, durability, and integrity of the network, and prevent negative impacts to appliances;

2. Conduct further R&D that considers the system integrity and durability at all levels of steels (low-, medium-, high-strength);

3. Study of the impact of integrity and durability as the blending percent and pressure increase;

4. Review and adopt the work by other international stakeholders; and

5. Test materials identified as compatible with H_2 in real-world setups to confirm their suitability further.

Conclusion for IM: The PRCI SOTA study concluded that in 2020, the industry consensus for gas transmission systems (pipelines) was that sufficient knowledge was available for up to 5% H_2 blending to be viable. However, case-by-case studies are needed to determine the appropriate blend percentage.

6.1.4 European NATURALHY Project (2004 - 2009)

In March 2010, a European consortium of 39 organizations published its final report[32] on the NATURALHY project, which ran for five and a half years from May 2004 through October 2009. The results clarified and elaborated on the feasibility of using the existing gas grid to transmit NG/H_2 mixtures. The research performed within the NATURALHY project did not identify any major barriers to adding H_2 at a useful level (up to 20% H_2 by volume) in the existing NG networks.

The NATURALHY project concluded that, from the safety, integrity, and durability point of view (safety considering pipeline operations and pipeline integrity; durability considering the life span of pipeline systems), the acceptable H_2 level can be significant (several tens of percent) depending on the mitigating measures taken by the operator. Such measures include:

- Material selection and coatings – resistant to hydrogen embrittlement and corrosion;
- Pipeline inspection and maintenance – detect and address potential issues early;
- Additives – gas mixture additives to mitigate hydrogen effects;
- Pressure management - adjust operating pressures to minimize stress; and
- Leak detection systems – quickly identify and respond to leaks.

The maximum allowable concentration of H_2 in a blend is determined by the safe use of an NG/H_2 mixture in buildings (severity of explosions) and the performance characteristics of some existing gas appliances. With safe use in buildings and properly adjusted conventional appliances, a limit of approximately 20% H_2 in the mixture would not lead to unacceptable consequences. However, for poorly adjusted appliances and/or unfavorable conditions of NG quality, no H_2 admixture should be allowed without mitigating measures.

One of NATURALHY project's deliverables was the Decision Support Tool (DST), which has two functions: (1) to inform what is expected in material and device behavior at different H_2 percentages and (2) to simulate, using its "what if" analysis, the actual pipeline degradation behavior over certain periods of time.

The analysis comprises risk assessment, cost assessment, evaluation, and proposal of rules, guidelines, and procedures that will mitigate the expected increase of risk and/or costs when applying the gas mixture to the pipeline network. It also provides a comprehensive toolbox that enables the user to simulate a Gas Technology Network (GTN) to enable comparisons between a GTN with or without H_2 addition. The DST is extremely flexible and can carry out GTN simulation and comparison of any two configurations over a period of up to 50 years, yielding cost, safety, and integrity calculations for all selected sections.

Figure 26 shows an example of the critical crack depth calculations made for a pipeline transporting different percentages of H_2 blended in NG.

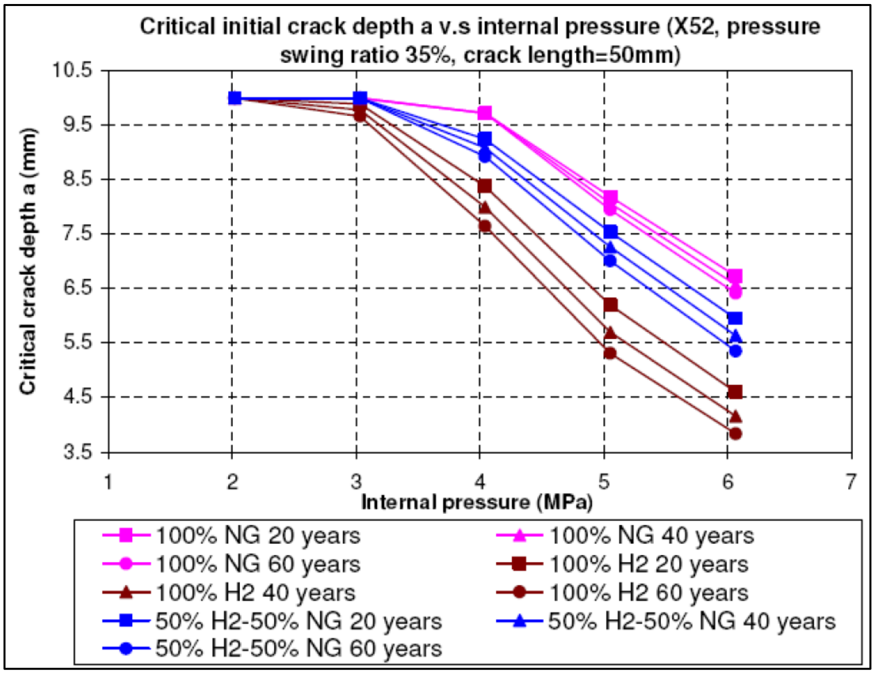


Figure 26. Example of Defect Criticality Calculations from NATURALHY Project[32]

6.2 Experience with Towngas

6.2.1 U.S. – 30%-50% H_2 Content in Towngas/Coal Gas (19th – Early 20th Centuries)

Towngas[33], also known as coal gas, was widely used for lighting, heating, and cooking in the U.S. during the 19th and early 20th centuries (see Figure 27). It was produced by heating coal without air, resulting in a mixture of H_2, CH_4, CO, and other gases. "The Hydrogen Energy," a digital platform for H_2 research, innovations, solutions, news, and events[34], references historical records that suggest the H_2 content could range from 30% to over 50% in some regions. The gas was delivered through municipal pipelines, like how NG is distributed today. However, the range was limited due to the technology at the time.

In the early 1800s, cities like Baltimore and New York began using towngas for street lighting. By the mid-1800s, it became common in many American cities, providing a cleaner alternative to burning raw coal. However, due to its toxic nature, towngas was eventually replaced by NG in the mid-20th century after vast NG reserves were discovered in the 1920s in the U.S.

Figure 27. One of the Uses of Towngas was Street Lighting

Today, towngas is used in Singapore, Hawai'i, and Hong Kong, as described in the following sections. For comparison, the nominal towngas composition delivered to clients in these regions is summarized in Table 2[35,36,37].

Table 2. Currently Used Nominal Towngas Compositions (Vol.%) in Different Regions.

Region	Gas	CH_4 (%)	H_2 (%)	CO_2 (%)	CO (%)	Other gases, incl. N_2 and O_2 (%)
Singapore	Towngas	30	50	15	3	2
Hong Kong	Towngas	28.2-30.7	16.3-51.8	16.3-19.9	1.0-3.1	0-3.3
Hawai'i	Blend of SNG and RNG	80-90	≤ 15	3	-	2

6.2.2 Singapore – Up to 50% H_2 Blended in Towngas (1861 - Present)

City Energy Pte, Ltd (formerly known as City Gas Pte Ltd, and founded as Singapore Gas Company in 1981) is the producer and retailer of piped towngas for residential, commercial, and industrial customers in Singapore[38]. City Energy provides town gas pipe installation and town gas supply activation services. The company also offers the maintenance and retail of gas appliances and solutions.

City Energy has a production facility in Singapore, Senoko Gasworks, equipped with a capacity of 1.6 million m^3/day. This is the sole facility producing towngas in Singapore. The production SMR uses NG and virgin naphtha as feedstock. The towngas is a mix of H_2 and CH_4. City Energy uses the gas pipeline network owned by PowerGas, a subsidiary of Singapore Power Group (SP Group), to supply towngas to its customers.

Since February 2017, SP Group has been Singapore's state-owned electricity and gas distribution company. Its precedent was Singapore Power, which was founded in October 1995. SP PowerGas is the sole licensed gas transporter and gas system operator, transporting both NG and towngas. It owns, operates, and maintains all the gas pipelines in Singapore and is responsible for delivering gas to users through its gas pipe network.

SP PowerGas operates a towngas system separate from the NG system.

- Towngas is supplied to 900,000 residents and commercial and industrial customers island-wide. The towngas transmission network operates at 45 psig (3 barg), whereas the distribution network operates at pressure regimes ranging from 0.1 psig to 8 psig (1 kPag to 50 kPag).

- NG is supplied to approximately 200 commercial and industrial customers and is imported from four sources (two submarine pipelines from Indonesia, one submarine pipeline from Malaysia, and internationally through the liquid natural gas (LNG) terminal.) The NG transmission network operates at two pressure regimes, 406 psig (28 barg) and 580 psig (40 barg), and the NG distribution network operates at pressures from 44 psig to 87 psig (3 barg to 6 barg).

In September 2022, the Hydrogen Industry Leaders (HIL) media platform announced on its website[39] that Singapore is set to have its first H_2-ready power plant by 2026. The Keppel Sakra Cogen Plant on Jurong Island[40] will have a combined-cycle gas turbine (CCGT) that can operate on a blend of H_2 and NG (see Figure 28). Following Singapore's Green Hydrogen Vision[41], the plant will initially use NG but is designed to operate on fuels with up to 30% H_2 content, potentially running entirely on H_2 in the future.

Figure 28. Keppel Sakra Cogeneration Plant will be in Sakra Sector of Jurong Island, Singapore[40]

In 2026, Singapore plans to incorporate green H_2 and ammonia (NH_3), produced using electrolyzers, into the towngas. Some of the green gases will be supplied by Malaysian oil company Petronas' renewable energy arm Gentari and AM Green, which produces NH_3 and green H_2. It is anticipated that it might take a year or two before the existing infrastructure is ready for Singapore to receive green NH_3.

Conclusion for IM: Singapore has 100+ years of experience with H_2/CH_4 gas blends and "towngas", containing approximately 50% H_2. In 2026, the country will have an H_2-ready power plant for up to 30% H_2 blended gas. Also, starting in 2026, Singapore plans to incorporate H_2 and NH_3 in its towngas.

6.2.3 Hong Kong – Towngas Containing 50 % H_2 (1862 – Present)

Hong Kong's towngas system, managed by the Hong Kong and China Gas Company Limited (Towngas)[42], is a supply network serving the region since 1862. Towngas is one of the largest energy suppliers in Hong Kong, providing gas to both residential and business customers. This system includes 2,300 miles (3,700 km) of underground gas pipelines.

The towngas is produced at two main plants: 79% is made at the Tai Po Gas Production Plant and 21% is made at the Ma Tau Kok Gas Production Plant. The towngas feedstock is a mix of naphtha and NG. Production involves the catalytic rich gas (CRG) process, which includes desulphurization, steam methane reforming (SMR), a water gas shift reaction, and CO_2 removal. The resulting syngas contains approximately 50% H_2, 30% CH_4, and 18% CO_2.

In 2023, Towngas installed an H_2 extraction system[43] at the Tai Po Gas Production Plant to extract H_2 directly from the existing gas network using pressure swing adsorption technology. This H_2 achieves a purity of up to 99.99% and can be used for fuel cell power generation and other applications. Figure 29 shows a photograph of the H_2 extraction facility.

Figure 29. H_2 Extraction Facility at Tai Po Gas Production Plant, Hong Kong[45]

Conclusion for IM: The Towngas company in Hong Kong has 150+ years of experience with gas blends, consisting of a mix of 50% H_2, 30% CH_4, and 18% CO_2. The company also operates an extraction system to separate H_2 from the towngas, which achieves 99.99% pure H_2 for use in fuel cells.

6.2.4 Ref. CPUC-1 - U.S. – Hawai'i Gas – Towngas with up to 15% H_2 in the Fuel Mix (1974 - Present)

In 1974, the Hawai'i Gas SNG Plant was built on the island of O'ahu[44] (see Figure 30). Since Hawaii has no naturally occurring NG, Hawai'i Gas produces SNG from naphtha, a petroleum byproduct sourced from two crude oil refineries in O'ahu.

While SNG is created artificially, its properties are like that of NG. Hawai'i Gas also produces RNG/biogas/biomethane[45] from decomposing organic matter from the City and County of Honolulu's Honouliuli Wastewater Treatment Plant on O'ahu (see Figure 31). Since 2014, Hawai'i Gas has received[46] containerized LNG as a backup fuel source for the SNG plant.

Figure 30. O'ahu SNG Plant[44]

Figure 31. Honouliuli RNG Facility Equipment[45]

The as-produced SNG contains up to 15% H_2. Downstream from the SNG plant, it is blended with RNG. That fuel mix is distributed to residential and commercial customers through an underground pipeline network of 1,100 miles (1,770 km) on O'ahu. This includes a 16-inch diameter transmission pipeline that connects the SNG plant with the utility distribution system. Hawai'i Gas is actively engaging in international H_2 research initiatives and has undertaken development projects to enhance the incorporation of alternative fuel into its supply mix.

Hawai'i Gas[47] describes its natural gas blend with up to 15% H_2 as supporting greater decarbonization. The company states that while its system is regularly tested and safe, H_2, at higher concentrations and pressures, can put infrastructure at risk for hydrogen embrittlement.

Hawai'i Gas uses a nanocomposite surface treatment named "Hydropel" produced by Oceanit[48] to prevent hydrogen embrittlement in pipes. Oceanit explains that the Hydropel surface treatment works by creating a passivating barrier that H_2 molecules cannot penetrate. The Hydropel coating can be applied in-situ to the walls of existing pipelines, forming this protective barrier between the gas and the metal, thus lowering the risk of embrittlement, fracture, and explosions associated with transporting H_2.

Conclusion for IM: Hawai'i Gas utility company has 50+ years of experience with CH_4 gas blends, consisting of a mix of SNG and RNG with up to 15% H_2, and reports on successful and safe operations. One technology applied to minimize hydrogen embrittlement risk is a nanocomposite surface treatment on the internal surface of pipelines.

7 H_2 BLENDING PROJECTS

Data on H_2 blending projects was gathered from several resources:

- The Hydrogen Incident and Accident Database (HIAD);
- The ARIA database (France);
- The U.S. Chemical Safety Board investigations;
- The International Energy Agency database;
- 2019 Power Magazine review of global power-to-gas projects[49];
- July 2022, California Public Utilities Commission (CPUC) Final Report from a Hydrogen Blending Impacts Study[50];
- PHMSA Pipeline Incident Reports;
- The Institute of Chemical Engineers (IChemE) database (U.K.); and
- HyResource (Australia).

7.1 HIAD Data

The European Commission (EC) Joint Research Centre (JRC), with the HySafe International Association for Hydrogen Safety, developed and maintains a Hydrogen Incident and Accident Database (HIAD) that is publicly available. The current version is HIAD 2.1.[51,52]

For the current research, the records from the HIAD Database were downloaded on November 14, 2024. At that time, 755 distinct H_2 incidents and accidents were included in the database. The data were sorted, and 58 records were selected for further review based on the occurrence of the words "pipeline," "pipe," "line," or similar terminology in the event descriptions. The team tasked by the EC to maintain the data was contacted. They provided additional information and references to those events that were available. A list of these selected projects referenced by the HIAD is given in Table 9.

Forty-nine (49) of the 58 pipeline-related incidents were initiated at the H_2 system. Nine were initiated at non-H_2 systems. The descriptions of these 49 incidents were analyzed to evaluate their applicability to the present research. Many documented incidents occurred not on pipelines but at industrial process facilities that use H_2, such as refineries, chemical plants, and foundries. The cases occurred in various situations, most related to facility piping. These generally involved 100% H_2 streams and/or chemicals processed with H_2, such as hydrocarbons, H_2S, hydrogen chloride (HCl), hydrogen fluoride (HF), and NH_3. The incidents' direct (metallurgical) cause was rarely related to hydrogen embrittlement phenomena and was usually associated with other integrity threats, such as external corrosion or mechanical damage.

Only one case of blended H_2 gas in a pipeline was found, HIAD Event ID 665, described below. Other case descriptions and a table listing the 49 cases are provided in APPENDIX A – HIAD and ARIA Case Descriptions Involving H_2, But Not Applicable to Blended H_2 Pipelines.

- HIAD Event ID 665 (IChemE No. 114961997[53]) – Hydrocarbons release from a pipeline
    - On January 1, 1997, a release and ignition occurred on a European pipeline (country not specified). The pipeline carried a flammable mixture of hydrocarbons and H_2. One person was killed and 46 people were injured. The root cause could be attributed to "an inadequate management system". An investigation into the incident found that management and supervisory staff did not make sure that emergency procedures were followed."
    - The HIAD database lists the failure causes as "job factors" and "management factors."
    - An inquiry was placed with the Royal Society of Chemistry, asking for the original IChemE reference, "Chemical Hazards in Industry" to get more information regarding this incident, and the following response was received: *"Chemical Hazards in Industry was one of our Literature Alerting Services that is now discontinued. Unfortunately, we are not able to provide content from these discontinued services."*
- *A leak occurred on a blended gas with H_2 transmission pipeline: The direct cause of the leak was not specified, while the root cause was attributed to an inadequate management system.*

7.2 The ARIA Database (France)

BARPI (French acronym for Bureau for Analysis of Industrial Risks and Pollutions), within the Ministry of Environment / General Directorate for Risk Prevention, is tasked with compiling, analyzing, and disseminating information and experience feedback on industrial and technological accidents.

The Analysis, Research, and Information on Accidents (ARIA) database catalogs incidents or accidents that were or could have been deleterious to human health, public safety, or the environment. ARIA has inventoried over 46,000 accidents and incidents occurring in France and abroad. The ARIA database is an accident database where operators of industrial facilities and inspection services can anonymously report an accident. The objective of the ARIA tool is to expand and render more reliable the data made available to the public through diverse sources of information.

The ARIA database was queried for incidents involving hydrogen. The pertinent records were also recorded in the above-described HIAD database. No other cases involving blended H_2 pipelines were found. The ARIA numbers and descriptions are provided together with the HIAD description in APPENDIX A – HIAD and ARIA Case Descriptions Involving H_2, But Not Applicable to Blended H_2 Pipelines.

7.3 The U.S. Chemical Safety Board Investigations

The U.S. Chemical Safety Board (CSB) is an independent federal agency charged with investigating industrial chemical accidents. The CSB conducts root-cause investigations of chemical accidents at fixed industrial facilities.

On the CSB website, www.csb.gov, 124 completed and eight ongoing investigations are documented. The reports are searchable by city, state, company name, and incident type. When searching for hydrogen-related investigations, cases involving H_2S, HCl, and HF came up, but no "pure" or "blended" H_2 incidents were found. The CSB concentrates on the safety of chemical facilities (which have process piping) but not the transportation of gas by transmission and distribution pipelines, which is under the purview of PHMSA.

The CSB described one case involving H_2, but it did not apply to blended H_2 pipelines (see APPENDIX B – CSB Case Description Involving H_2, But Not Applicable to Blended H_2 Pipelines).

7.4 The International Energy Agency (IEA) Database

The International Energy Agency (IEA) maintains an H_2 production and infrastructure project database[54]. The database tracks data to produce H_2 for energy or climate-change mitigation purposes and the development of H_2 infrastructure. The data are available for free. Two separate database files were downloaded for this project in November 2024.

- The IEA Hydrogen Infrastructure Database – projects by type
    - 151 Pipelines
    - 41 Blending
    - 43 Underground gas storage (UGS)
    - 19 H_2 port
    - 96 NH_3 port
    - 20 NH_3 cracking
    - 8 Methanol port
        - **TOTAL: 378 PROJECTS**
- The IEA Hydrogen Production Projects Database
    - 644 Concept
    - 7 Decommissioned
    - 245 Demonstration (DEMO)
    - 891 Feasibility Study
    - 297 Final Investment Decision (FID)/Construction
    - 334 Operational
    - 16 Other/unknown
        - **TOTAL: 2,434 projects**

7.4.1 IEA H_2 Infrastructure Database

Of the 151 pipeline projects, only one is operational. However, the project involves a 100% H_2 transmission pipeline without H_2 blending. A description of this project is included in APPENDIX C – IEA Project Descriptions Involving H_2, But Not Applicable to Blended H_2 Pipelines.

Within the 41 H_2 blending infrastructure projects, 19 are operational (IEA Infra. Data Ref. BLE-29 was a duplicate of BLE-26), while the others are in various other stages of development (see Table 3.) Sorted lists of H_2 production and infrastructure projects referenced by the IEA are given in Table 4 (H_2 blending projects), Table 10 (H_2 for any purpose), and Table 11 (H_2 for grid injection) in APPENDIX C – IEA Project Descriptions Involving H_2, But Not Applicable to Blended H_2 Pipelines.

Table 3. Status of Global Blending Projects for Hydrogen Gas for Any Purpose, from IEA Hydrogen Production and Infrastructure Projects Database, as of November 2024[54]

STATUS	2013	2016	2017	2019	2020	2021	2022	2023	2024	2025	2026	2028	2030	Blank	Total
Concept										2	2		1		**5**
Feasibility Study							1		1				1		**3**
Demonstration				1	1		1								**3**
Under Construction								1	1			1		1	**4**
Operational		1	1	1		5	7	4	1						**20**
Cancelled								1	1	1					**3**
Decommissioned	1			1		1									**3**
Blank															
Total	**1**	**1**	**1**	**3**	**1**	**6**	**9**	**6**	**4**	**3**	**2**	**1**	**2**	**1**	**41**

Table 4. Partners, Locations, % Blend, and Announced Size of Global Blending Projects for Hydrogen Gas for Any Purpose, from IEA Hydrogen Production and Infrastructure Projects Database, as of November 2024[54]

IEA Ref.	Project	Partners and Location	Online	H_2 Blend	Announced Size	Lit. Refs.
BLE-1	HyP SA-Hydrogen Park South Australia	Australian Gas Networks (Tonsley Innovation District, Australia)	2021	5-10%	1.25 MW electrolyzer, 700 customers by pipeline + other uses by truck	111, 112, 113
BLE-2	Western Sydney Green Gas	Jemena (Sidney, Australia)	2021	2%	23,500 residential, 100 commercial, and 7 industrial	55, 56, 57
BLE-4	Community Blending Project - Western Australia	ATCO (Cokburn, Australia)	2022	2-5% (10% by 2030)	2,700 connections, 175kw	114
BLE-7	Fort Saskatchewan hydrogen blending project	ATCO (Fort Saskatchewan, Canada)	2022	NA	2,100 customers	115
BLE-8	Hydrogen-blending pilot in Markham	Enbridge Gas, Cummins (Markham, Canada)	2022	NA	3,600 consumers	116
BLE-9	Gasvalpo Energas Coquimbo	Gasvalpo (Coquimbo, Chile)	2022	5-20%	>2,000 homes	117
BLE-10	Promigas, Surtigas-Heroica	Promigas, Surtigas (Cartagena, Colombia)	2022	NA	1.6 t H_2/yr (15 t H_2/yr in next pilot phase)	118, 119, 120
BLE-12	WindGas Haßfurt	WindGas Haßfurt (Germany)	2016	4-5%	14,000 customers	121, 122

IEA Ref.	Project	Partners and Location	Online	H_2 Blend	Announced Size	Lit. Refs.
BLE-13	Freiburg Municipal Energy Network	Freiburg Municipal Energy Network (Freiburg, Germany)	2017	2%	200 kW electrolyzer	123
BLE-14	Wind2Gas Energy	Wind2Gas Energy (Brunsbüttel, Germany)	2019	2%	2.4 MW electrolyzer	58, 59
BLE-15	Green Hysland	Redexis, Enagás (Mallorca, Spain)	2024	2%	2.5 MW electrolyzer	60
BLE-21	Hydrogen Blending in Indore	GAIL, HPCL--Avantika Gas Limited (Indore, Madhya Pradesh, India)	2022	2%	NA	124
BLE-22	NTPC-GGL in Surat	NTPC, Gujarat Gas (Kawas township at Adityanagar, Surat, India)	2023	5% scaled to 20% in future	200 customers	125
BLE-23	Floene Seixal	Floene, Seixal City Council, Bosch, Catim, Gestene, ISQ, PRF, Higher Technical Institute and HP2H (Seixal, Portugal)	2023	20%	82 customers	126, 127
BLE-24	20HyGrid	Delgaz Grid (E.ON Romania group) (Dârlos, Romania)	2023	20%	75 customers	130
BLE-25	CenterPoint Energy	CenterPoint Energy (Minneapolis, USA)	2021	5%	432 kg H_2/day	133, 134
BLE-26	Therm H2	Dominion Energy (Salt Lake City, USA)	2021	5%		135
BLE-27	Blending in New Jersey	New Jersey Resources Corp. (Howell, NJ, USA)	2021	1%	65 kg H_2/day	61
BLE-28	HyGrid - Long Island	National Grid, Town of Hempstead (Hempstead, USA)	2022	5-20%	800 homes	136, 137

The following paragraphs describe the operational projects involving H_2 blending and transmission pipelines. The percentage of H_2 in the various blend projects varies based on the constraints encountered and their developers' choices. Projects that do not involve all three of these aspects are included in APPENDIX C – IEA Project Descriptions Involving H_2, But Not Applicable to Blended H_2 Pipelines.

7.4.1.1 IEA Infra. Data Ref. BLE-2 / IEA Prod. Data Ref. 737 – Jemena Green Gas – H2GO Project – Horsley Park, Western Sydney, Australia (2% H_2/NG)

- In 2021, Jemena, an electrical and gas utility company, started a renewable gas pilot production facility in Horsley Park, Western Sydney[55,56,57]. The Western Sydney Hydrogen Hub (WSHH) produces H_2 with a 500 kW onsite electrolyzer, using offset green power from the electrical net (see Figure 32).

- The Australian Renewable Energy Agency (ARENA) co-funds this project.

- Once H_2 is injected into the existing gas network and blended with NG, the gas mixture can be used by homes and businesses in the surrounding areas of Western Sydney.

- Jemena owns and manages significant gas and electricity assets in Australia, including a gas network that supplies 1.4 million customers in New South Wales.

- The Western Sydney Green Gas Project involves a trial power-to-gas facility that will transform (surplus) renewable electrical energy into H_2 gas for blending in a gas network, storage, power generation, and potentially mobility and industrial applications.

- A 500kW Proton Exchange Membrane (PEM) electrolyzer, using purchased renewable power, converts mains water and/or reverse osmosis (RO) quality recycled water into H_2 and O_2, with the latter being vented. The produced H_2 is injected and blended with NG into the existing Jemena natural gas distribution network at up to 2% by volume via a dedicated injection control panel.

- This project is at the Jemena-owned Horsley Park high-pressure gas facility in Western Sydney. The Horsley Park complex is connected to two major pipelines that supply natural gas to Sydney and New South Wales: the Central Trunk Pipeline and the Eastern Gas Pipeline. No modifications to the existing pipeline infrastructure are required at the proposed blending concentration.

- The project began blending H_2 into the gas network in November 2021 and is anticipated to operate for approximately five years.

- Jemena reports the following milestones on this project:

    - October 2018: ARENA announced funding of AUD $7.5 million for Jemena to build a demonstration-scale 500 kW electrolyzer at its facility in western Sydney.

    - August 2020: Development approval received under the Planning System Acceleration Program.

    - May 2021: Construction completed; commissioning commences.

    - November 2021: The project begins blending H_2 into the New South Wales gas network.

    - June 2022: Hydrogen has been produced at the Western Sydney facility and blended into the Jemena gas network. Several tests have been conducted to test the facility's performance, and the accuracy of these tests has been validated through gas sampling and testing. Testing of the facility is ongoing and still in progress.

- August 2024: Another extensive series of H_2 blending and validation tests have commenced, including ascertaining, via sampling, the blending consistency of the H_2 as it is distributed along/within the local gas network.

- *This project is operational and involves a 2% H_2/NG blend and two major gas transmission pipelines.*[6]

Figure 32. Delivery of Electrolyzers for Western Sydney Green Gas Project, Australia[57]

7.4.1.2 IEA Infra. Data Ref. BLE-14 / IEA Prod. Data Ref. 68 / CPUC-15 – Wind2Gas Energy – Brunsbüttel, Schleswig-Holstein, Germany (up to 2% H_2/NG)

- In 2019, Wind2Gas Energy started operating a 2.4 MW PEM electrolyzer to produce H_2 for Greenpeace Energy[58] at the Südermarsch plant in Brunsbüttel, Schleswig-Holstein, Germany (see Figure 33).

- Hydrogenics Corporation supplied the electrolyzer in an agreement with Wind to Gas Südermarsch GmbH & Co. KG[59].

- H_2 production is powered by surplus electricity from a 15 MW wind farm nearby. However, this wind-strong location experiences many fluctuating conditions.

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[6] To follow the scope and objectives of the current research, this report uses green (yes) and red (no) fonts to indicate if a project is (1) operational, (2) involves H2 blending, and (3) involves a transmission pipeline.

- H_2 can be fed into the nearby NG pipeline. The current admixture share is approximately 2% H_2, but in the next few years, a higher proportion of H_2 is to be added.

- H_2 is also available as fuel at nearby H_2 filling stations next to the electrolysis plant.

- *This project is operational, involves a 2% H_2/NG blend, and has a gas transmission pipeline.*

Figure 33. Südermarsch Hydrogen Blending Facility in Brunsbüttel, Schleswig-Holstein, Germany[58]

7.4.1.3 IEA Infra. Data Ref. BLE-15 – Green Hysland – Mallorca, Spain (up to 2% H_2/NG)

- In 2024, Redexis began blending H_2 into the gas network on the island of Mallorca, Spain[60], as part of the "Green Hysland" initiative. H_2 is produced in the Mallorcan town of Lloseta (see Figure 34).

- The infrastructure will benefit 115,000 households and 2,000 tertiary and industrial consumers. All consumers connected to the 870 miles (1,400 km) of the operational NG networks in Mallorca will be able to access the gas.

- The facilities include a 2.0-mile (3.2 km) H_2 pipeline and a mixer that allows H_2 to be injected into the NG network. The H_2 pipeline runs from the reception point to the primary transmission pipeline San Juan-Cas Tresorer-Sus. The static mixer injects the volume of H_2 required into multiple high-speed NG flows, which are collected at the steering room output to provide high uniformity of the gas composition and low turbulence.

- Currently, 2% H_2 is injected into the NG network, allowing 100% of the production of the Lloseta plant to be evacuated. Both the network and the final equipment installed are prepared to inject higher amounts - between 10 and 20% - without making any modifications.

- *This project is operational, involves a 2% H_2/NG blend, and has a gas transmission pipeline.*

Figure 34. Visitors at Hydrogen Blending Facility in Mallorca, Spain[60]

7.4.1.4 IEA Infra. Data Ref. BLE-27 – NJNG's Green Hydrogen Blending Project – Howell, NJ, United States (up to 1% H_2/NG)

- In October 2021, New Jersey Natural Gas (NJNG)[61] reached commercial operation of a green H_2 production facility in Howell, NJ (see Figure 35).
- This project uses a 175 kW electrolyzer with excess wind power during periods of low demand to produce up to 65 kg/day of green H_2.
- H_2 is blended directly into an existing gas distribution system, powering homes and businesses. H_2 injection is received in an 8-inch diameter, 60 psig pressure distribution pipeline.
- *This project is operational, involves up to 1% H_2/NG blend, and has an 8-inch diameter pipeline.*

Figure 35. NJNG Howell, NJ, Site with Hydrogen Facilities[61]

7.4.2 The IEA Hydrogen Production Projects Database

Table 11 shows a global list of 32 current (2024) operational H_2 gas production projects for grid injection (H_2 blending). The following sections describe operational projects not described elsewhere in this report that involve H_2 blending and transmission pipelines. Projects that do not involve all three of these aspects are included in APPENDIX C – IEA Project Descriptions Involving H_2, But Not Applicable to Blended H_2 Pipelines.

7.4.2.1 IEA Prod. Data Ref. 202 – First WindGas Project – Falkenhagen, Prignitz, Brandenburg, Germany (up to 2% H_2/NG)

- Uniper SE (the former generation business of utility company E.ON spun off in January 2016) has hosted two major pilot projects to produce green H_2 and CH_4 from wind power at its site in Falkenhagen, Germany[62,63,64] (see Figure 36).

- In October 2011, the first "WindGas Falkenhagen" demonstration project started by E.ON came to fruition after securing a partnership with gas distributor, Swissgas.
    - This project used an H_2 production facility, which included a 2 MW containerized alkaline electrolyzer, gas compressor, and master controls, to convert wind power to gas (PtG).

- The plant produced up to 360 normal m^3 of H_2 that was fed into a 1.2 miles (2 km) long NG pipeline at approximately 2% by volume, at an MOP of 800 psig (55 barg).
- Ultimately, in August 2013, H_2 sourced from 1 MW of wind power was fed into the local gas grid operated by ONTRAS Gastransport GmbH.

- *This project is operational, involves a 2% H_2/SNG blend, and has a transmission pipeline.*

Figure 36. Top of Reactor and Economizer, with Trench for H_2 and SNG Pipeline to Existing Plant Visible in the Background - Falkenhagen, Germany[62]

7.4.2.2 IEA Prod. Data Ref. 142 / PM Ref. 13 - PtG Project – Hamburg-Reitbrook, Germany (unspecified % H_2/NG)

- In April 2013, a second PtG project by E.ON, called "WindGas Hamburg-Reitbrook" moved forward. It came online in October 2015 in Hamburg, Germany[65] (see Figure 37).
  - This project produces green H_2 with a 1.5 MW PEM electrolyzer stack for injection into the NG grid.
    - This PEM electrolyzer has a power density four times that of the above-mentioned alkaline electrolyzer in Falkenhagen, Prignitz.
  - After creation, the H_2 gas in Hamburg-Reitbrook is compressed to 217 psig (15 barg) before being fed into the NG distribution network.
  - The German Aerospace Center has been testing the degradation of individual components as part of the scientific research accompanying this project. So far, the analyses have concluded that "despite a first stress test, we have not yet found any signs of aging."

- *This project is operational, involves an unspecified H_2/NG blend, and has a transmission pipeline.*
- *This is one of the few projects that aims to address the degradation and structural integrity of the components.*

Figure 37. Electrolyzer of PtG Project in Hamburg-Reitbrook, Germany[65]

7.4.2.3 IEA Prod. Data Ref. 437 / PM Ref. 10 - Energiepark - Mainz-Hechtsheim, Germany (unspecified % H_2/NG)

- Following its initial announcement in 2013, in February 2015, the then-largest green H_2 plant in the world was commissioned in Mainz-Hechtsheim, Germany[66,67,6869] (see Figure 38 and Figure 39).
- The energy park was designed to produce H_2 using surplus electricity from neighboring wind parks using a 6 MW PEM-based high-pressure electrolyzer.
- The H_2 is purified, compressed, stored, and distributed.
- The produced H_2 is stored on-site and partly loaded into tankers to supply H_2 fueling stations (for vehicles). Some H_2 is also fed into the NG grid for heating or power generation.

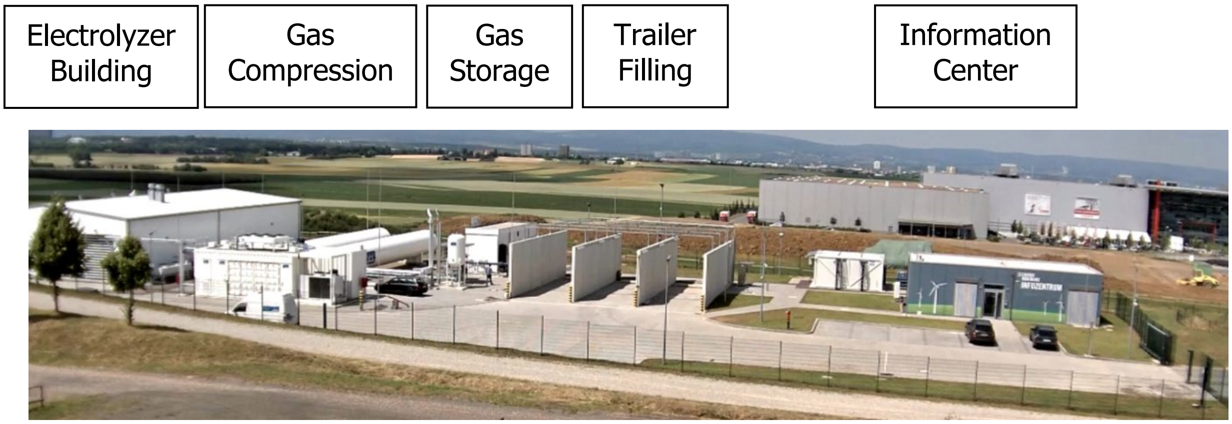

Figure 38. Energiepark in Mainz-Hechtsheim, Germany[67]

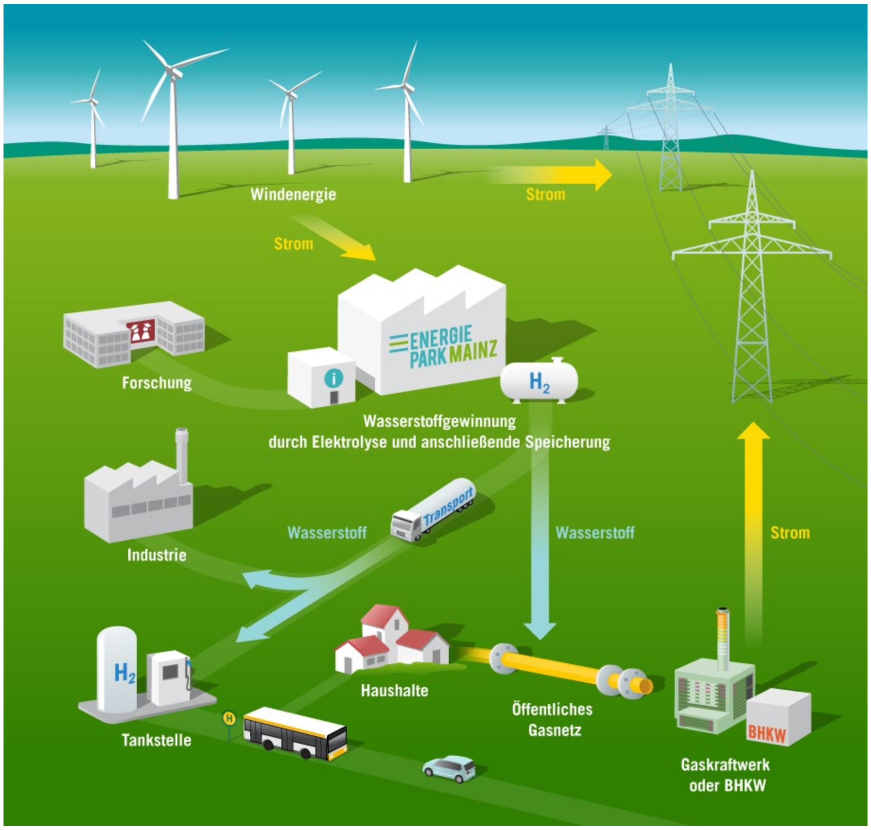

Figure 39. Schematic of Energiepark in Mainz-Hechtsheim, Germany, Showing H_2 is Distributed by Truck and by Gas Pipeline Network[68]

- *This project is operational, involves an unspecified H_2/NG blend, and has a transmission pipeline.*

7.4.2.4 IEA Prod. Data Ref. 80 - Windgas Haurup, 1st phase – Haurup, Schleswig-Holstein, Germany (up to 2% H_2/NG)

- In December 2020, Gasunie Deutschland and Open Grid Europe announced that for the first time, green H_2 converted in a PEM electrolyzer using surplus renewable electricity from wind turbines was fed into the gas transmission pipeline system in Haurup, Schleswig-Holstein, Germany[70,71,72] (see Figure 40).

- Up to 2% H_2 is blended into NG in the DEUDAN pipeline, which stretches from the German-Danish border crossing at Ellund to Quarnstedt in Schleswig-Holstein.
  - The pipeline is existing infrastructure.
  - The pipeline is approximately 62 miles (100 km) in length.

- The project includes an H_2 blending facility with metering and pressure-regulating equipment, two independent compressor units to raise the H_2 pressure from the electrolyzer (35 barg [508 psig]) to the DEUDAN pipeline pressure (60 barg [870 psig]), and the construction of two connecting pipelines, each 250 feet (75 m) long.

- The electrolyzer has a capacity of 1 MW and can produce 7,400 standard ft^3/hr (210 standard m^3/hr) of H_2.

- *This project is operational, involves up to 2% H_2/NG blend, and has a transmission pipeline.*

Figure 40. Delivery and Interior View of Electrolyzer in Haurup, Schleswig-Holstein, Germany[72]

7.5 Power Magazine Data

In 2019, Power Magazine published a review of global power-to-gas (P2G) projects to date[49]. According to experts from the Ostbayerische Technische Hochschule (OTH) in Regensburg, Germany, who reviewed the world's existing power-to-gas H_2 and CH_4 projects, approximately 143 P2G projects have operated in 22 countries since 1988.

Only 56 hydrogen and 38 methanation projects were active in 2019. The projects that include grid injection are listed in Table 5.

While the then-existing fleet mostly comprised pilot or demonstration projects under 1 MW, nearly 45% of these projects fed or planned to feed gas into the grid or reconvert it into power or heat. A more detailed analysis is given in another Power Magazine article[73].

Selected projects from the Power Magazine list are described further in this report.

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Table 5. Global Power-To-Hydrogen Gas Projects for Grid Injection, According to Power Magazine, as of September 2019[49]

PM Ref.	Project Name	Country	Online	Electric	Transport	Lit. Ref.
1	Ameland Island	Netherlands	2008	0.009	5 to 20% H_2/NG Blend for distribution by pipeline (14 homes)	74
2	Hybridkraftwerk Prenzlau	Germany	2011	0.6		138, 139
3	GRHYD – Dunkerque	France	2013			75, 76
4	PtG-Etzel	Germany	2013	6		
5	RH2-WKA – Grapzow	Germany	2013	1		
6	Designetz Pilotanlage Ibbenbüren	Germany	2013	0.15		
7	w2h – Auersthal	Austria	2014	0.1		
8	PtG Berlin-Schöneberg	Germany	2014	0.007		
9	Thüga Strom zu Gas Plattform – Frankfurt	Germany	2014	0.3		
10	Energiepark Mainz	Germany	2014	6		66, 67, 68, 69
11	Power-to-Gas (for energy storage purposes) – Ontario	Canada	2014	0.005		
12	Agerbæk/Helle-Project	Denmark	2015	0.006		
13	WindGas Hamburg	Germany	2015	1		62, 63, 64
14	Underground Sun Storage – Pisbach	Austria	2015	0.6		
15	Stromlückenfüller – Reußenköge (1st Phase)	Germany	2015	0.2		
16	HYPOS: localhy - Sonneberg	Germany	2015	0.075		
17	Smart Power Farm – Cheshire	U.K.	2016	0.005		
18	WindGas Haßfurt	Germany	2016	1.25		121, 122
19	HyDeploy – Newcastle under Lyme	U.K.	2019	0.5		77, 78

7.5.1 Ref. PM-1 – Netherlands - Ameland Island (2008) – H_2 Enriched NG in an Apartment Complex

In the Ameland Island project[74], pipeline materials were tested using a reference grid and a test grid that was added to the existing NG grid (see Figure 41). The grid contained different pipeline materials for mains, joints, service governors, and gas meters. The selected pipeline materials and accessories were those commonly used in the Dutch gas network.

After four years of exposure, the different materials and joints were tested to determine whether their quality was comparable. In addition to a visual inspection of the pipes and joints, mechanical and chemical research was performed to determine whether any degradation from H_2-enriched NG exposure had occurred. The results showed that the most important properties of the examined pipeline materials from the reference and test sections showed no effects after four years of exposure to H_2-enriched NG.

Figure 41. The Hydrogen Supply, Blender, and Apartment Complex “Noorderlicht” on Ameland Island[74]

One of the concerns when distributing H_2 is the possible high amount of (atomic) hydrogen permeating through the pipeline wall. Therefore, some permeation tests were performed. The overall permeation was low and was not expected to lead to any (safety) problems. Eye-catching was that the permeation of an H_2/NG gas mixture has a lower permeation constant than H_2 gas only. Visual inspection did not identify hydrogen-related defects on the pipeline material.

In addition to the pipeline material, attention was paid to joints and other accessories like rubber hoses, service governors, and gas meters. For exposed and non-exposed joints, the quality was assessed by taking samples from the reference and the test sections. The hoses, service governors, and gas meters were assessed differently because these accessories were not installed in the reference section. In the case of service governors, the initial and final quality were measured and compared. The exposed gas meters and rubber hoses were compared to new non-exposed gas meters. The joints exposed to the H_2-enriched NG did not show any degradation, nor did the service governors and gas meters. Visual inspection did not identify hydrogen-related defects or pollution. Therefore, it was concluded that, for the test period of four years, the integrity of the grid, including pipelines and accessories, was not compromised by using H_2-enriched NG.

Conclusion for IM: After four years of exposure to H_2-enriched NG, the most important properties of the examined pipeline materials originating from the reference and test grids showed no detrimental effects.

7.5.2 Ref. PM-3 / Ref. CPUC-10 – France — GRHYD Demonstration - Dunkirk 6% up to 20% H_2 into Buses and 200 Residential Homes (2014)

In 2014, the GRHYD demonstration project was launched by a consortium of industrial partners led by ENGIE, an energy company. The project included a trial to inject of H_2 into the NG distribution network of a neighborhood, Le Petit Village, and a natural gas vehicle (NGV) refueling station for buses located in the Dunkirk urban community in France (see Figure 42). The blend of H_2 and NG was referred to as "Hythane." H_2 was produced using a Power-to-Gas concept, where the electric power was primarily obtained from renewable sources (wind power). The production was supplemented using surplus power (nuclear energy) to produce H_2 for storage and subsequent distribution to meet demand.

The project aimed to demonstrate this new energy solution's technical, economic, environmental, and social advantages. The timeline included two years of technical and sociological studies, followed by a five-year demonstration phase of two uses of H_2 injection: transport (50 buses; initially 6% H_2, then increasing up to 20% H_2) and housing (200 homes; up to 20% H_2).

Figure 42. Containers with Hydrogen Equipment for Dunkirk Pilot Project[75]

According to ENGIE[75,76] in 2020, the project was successful. The results of this R&D pilot project included good public acceptability subject to cost control, normal operation of gas appliances (domestic and residential boilers), regular discussions with the authorities regarding regulatory changes, and high interest, as evidenced by hundreds of French and international visitors to the site.

Conclusion for IM: After five years of exposure to up to 20% H_2/NG blended gas, there was public acceptance, and appliances could operate normally.

7.5.3 Ref. CPUC-18 / IEA Prod. Data Ref. 42 / Ref. PM-19 - U.K. — HyDeploy at Keele University (up to 20% H_2 blend)

7.5.3.1 HyDeploy (2016 - 2017)

A paper in the "Clean Energy" journal reported on the HyDeploy project[77], hosted at Keele University, funded under Ofgem's Network Innovation Competition (NIC), and executed as a collaboration between several industrial partners. HyDeploy was the U.K.'s first practical project to demonstrate that H_2 can be safely blended into the NG distribution system without requiring appliance changes and the associated disruption. The trial included 101 residential houses, 8 student halls, 17 office blocks & laboratories, and 7 recreational and service facilities.

The project consisted of three phases:

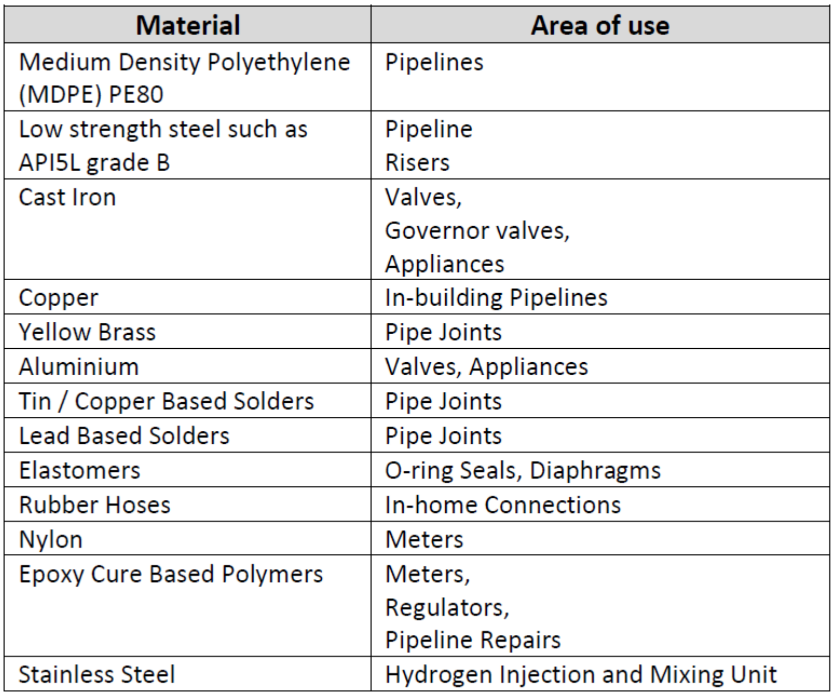
- Phase 1 - An 18-month technical program to build the evidence base to demonstrate that H_2 is safe to blend in the targeted gas network, with three main elements:
    - Laboratory work;
    - Network appliance testing; and
    - Risk analysis.
- Phase 2 - Construction of the electrolyzer, grid entry unit, sampling points to allow monitoring, and piping and valves
    - Construction, training, and networking preparation
- Phase 3 - A 10-month trial that started in the summer of 2019
    - 20 mol% in natural gas
    - Rigorous monitoring regimen, including the process equipment, network, and appliances.

Following the injection trial, the physical equipment was to be decommissioned and moved on, and the network was to be returned to NG operation.

In 2018, a report[78] on the material effects of introducing H_2 into the U.K. gas supply was submitted by the Health and Safety Executive's (HSE's) Health and Safety Laboratory (HSL).

Different materials identified as being present on the Keele University G3 Gas Distribution Network (GDN) were investigated to assess their possible reactions with blended H_2/NG. That investigation included a literature review and specific testing. The materials that were identified and tested are listed in Table 6.

Table 6. Materials in Keele University G3 Gas Distribution Network[78]



Material	Area of use
Medium Density Polyethylene (MDPE) PE80	Pipelines
Low strength steel such as API5L grade B	Pipeline Risers
Cast Iron	Valves, Governor valves, Appliances
Copper	In-building Pipelines
Yellow Brass	Pipe Joints
Aluminium	Valves, Appliances
Tin / Copper Based Solders	Pipe Joints
Lead Based Solders	Pipe Joints
Elastomers	O-ring Seals, Diaphragms
Rubber Hoses	In-home Connections
Nylon	Meters
Epoxy Cure Based Polymers	Meters, Regulators, Pipeline Repairs
Stainless Steel	Hydrogen Injection and Mixing Unit

At the time of the Clean Energy paper in May 2019, HyDeploy successfully completed Phase 1. Subsequently, the HSE granted the U.K.'s first exemption for H_2 injection into a gas network.

Conclusion for IM: No materials-related issues have been identified on Keele's network at operational pressures for NG containing up to 20 mol% H_2. HyDeploy has demonstrated that regulatory approval for H_2 blending up to 20 mol% is possible.

7.5.3.2 HyDeploy2 (2019 - Present)

Following HyDeploy, a larger public network application, "HyDeploy2", is being conducted as the connecting step between trial-scale deployment and commercialization. HyDeploy2 funding was confirmed in November 2018 and has the same project development team as HyDeploy. The strategic objective of HyDeploy2 is to bring H_2 injection to the same level of regulatory approval as biomethane injection. HyDeploy2 is carrying out two further trials over four years starting in 2019. It supplies approximately 1,500 households with 20% H_2 blended gas and undertakes extensive laboratory work.

In December 2023, the Department of Energy Security and Net Zero (DESNZ) made a significant decision[79] to proceed with H_2 blending, explicitly referencing the foundational work conducted by the HyDeploy project to date.

After completing the safety evidence, the U.K. government will decide whether to enable blending, including considering any implications from the safety assessment. The safety assessment will involve a review of the evidence by the HSE.

Enabling blending at scale will require amendments to legislation, including Gas Safety (Management) Regulations (GS(M)R), 1996, which currently limits H_2 content within existing gas distribution networks to 0.1 mol%. These regulations ensure the safe use and management of gas through the gas network in the U.K. If the outcomes from the safety review and subsequent economic assessment support a future decision for H_2 blending, the U.K. government will then look to start the legislative process to implement amendments.

7.5.4 Ref. CPUC-3 - U.S. — SoCalGas and UC Irvine — Blending H_2 made from Excess Renewable Electricity to Campus Pipeline (2016; Proposed for 2025)

SoCalGas and the University of California, Irvine (UCI) conducted their first successful blending demonstration on campus in 2016. At present (2025), at the direction of the California Public Utilities Commission (CPUC), SoCalGas is proposing a local demonstration project that could safely blend up to 20% renewable H_2 into the NG system in an isolated portion of the UCI campus. The project will be at the UCI's Anteater Recreation Center (ARC). This is part of a broader effort by California and Utilities to develop a standard for safe H_2 blending. Figure 43 shows a schematic of the H_2 blending setup at UCI.

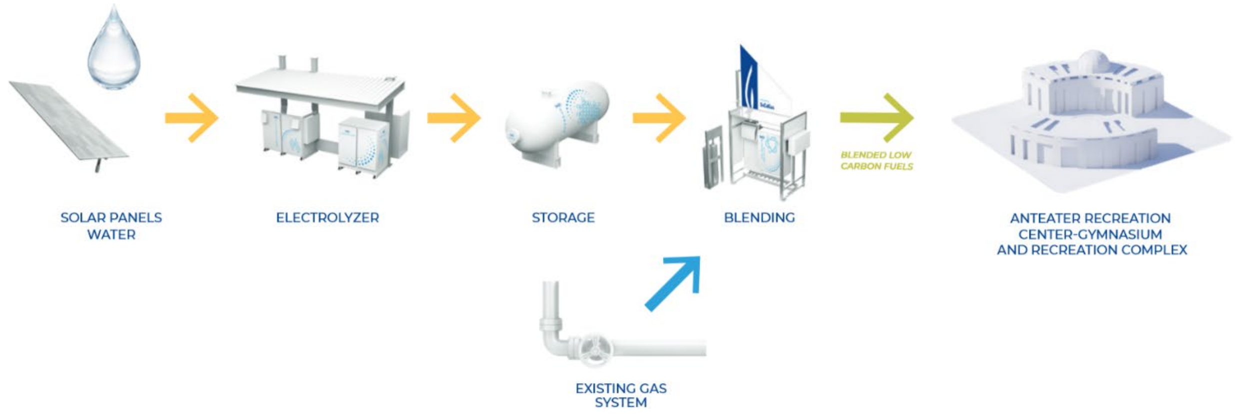


Figure 43. How H_2 Blending Will Work on the UCI Campus[80]

The proposed project[80, 81] will demonstrate a 5% H_2 blend, gradually increasing up to 20%. The H_2 blend will serve light commercial equipment. Active blending is expected to last approximately two years (2026-2028) on campus. The project will include the following safety protocols:

- Extensive H_2 safety training for personnel;
- Development of blending protocols and emergency response plans;
- Operational tests and equipment tests to confirm that the gas system and equipment are free of leaks and prepared to receive an H_2 blend prior to the introduction of H_2;
- Rigorous safety assessments of H_2 storage and H_2 components;
- Thorough inspections of behind-the-meter equipment to confirm that it is free of leaks and operates safely;
- Continuous leak monitoring, including monthly surveys (which is 12 times the normal protocol of leakage inspection);
- Installation of remote CH_4/H_2 monitoring systems; and
- Stringent measures to prevent H_2 or H_2 blends from reaching natural gas storage areas or electrical switching equipment.

Conclusion for IM: It will take several years before materials and equipment performance information from the UCI H_2 blending project will become available to the public.

7.5.5 Germany - E.ON/Avacon - Trial of 350 Customers Supplied with 10%, 15%, 20% H_2 Blend (2021 - 2023)

A technical standard in Germany limits the H_2 concentration in NG networks to a maximum of 10%. However, E.ON has conducted several trials with higher concentrations of H_2 admixtures in NG.

In an October 2021 joint press release[82], E.ON, its subsidiary Avacon, and Deutscher Verein des Gas- und Wasserfaches e.V. (DVGW) announced that Avacon would start adding H_2 to a sub-grid in Saxony-Anhalt. The network section is a medium-pressure distribution network with a pipeline length of approximately 22 miles (35 km), from which 350 network customers are supplied with NG.

Step by step, 10%, 15%, and 20% H_2 would be added to the NG during the winter heating periods of 2021-2022 and 2022-2023. Prior laboratory testing showed that many household appliances can operate with up to 30% H_2 admixture. All appliances were tested with test gas that already contained 23% H_2 as part of the approval process. Figure 44 shows a photograph of the blending equipment used[83].

Figure 44. Equipment for Blending H_2 Into NG[83]

As described later in this report, in 2020-2023, E.ON followed up with a trial with 100% H_2 by converting an existing, medium-pressure pipeline in Holzwickede in North Rhine Westphalia State.

7.6 CPUC Data

In July 2022, CPUC issued a final report from a Hydrogen Blending Impacts Study[50], prepared by the University of California, Riverside. A list of projects referenced by the CPUC is given in Table 7.

7.6.1 Ref. CPUC-16 - Italy — Snam 5% H_2 into Gas Transmission Network (2019)

In 2019, in Contursi Terme in the province of Salerno in southern Italy, Snam[84], a gas utility company, started introducing a blend of 5% H_2 in NG into their gas transmission network to supply two industrial customers (a pasta factory and a mineral water bottling company) (see Figure 45). Snam reported on its website[85] that the project consisted of a one-month trial and was successful. In December 2019, Snam[86] doubled the volume of H_2 in the blend to 10%.

Figure 45. Team Involved in the Contursi Terme Project[85]

Snam is Europe's leading gas utility and has been in business for 75 years. Snam operates in Italy and, through subsidiaries, Austria (TAG and GCA), France (Teréga), and the United Kingdom (Interconnector U.K.). Snam is one of the main shareholders of the Trans Adriatic Pipeline (TAP). Snam participates in various national and international efforts, including:

- Member of H2IT – Italian Hydrogen and Fuel Cells Association;
- European Hydrogen Initiative – Declaration by companies to support H_2 and its broad potential as a sustainable technology;
- HYREADY Network – Making existing gas transport networks compatible with the injection of increasing percentages of H_2; and
- Hydrogen Council – A coalition of leading companies to accelerate H_2 investments.

Snam states that if 5% H_2 were added to the total gas transported annually by Snam, 3.5 billion m^3 could be added to the network each year. This is equivalent to the annual consumption of 1.5 million households, which would allow CO_2 emissions to be reduced by 2.5 million tons.

As of January 2025, Snam states on its website that the company is committed to verifying the full compatibility of its infrastructure with increasing amounts of H_2 mixed with NG, as well as studying H_2 production from renewable electricity. By the end of the year, the experiment will be repeated on the same part of the network, bringing the amount of H_2 in the mix supplied to the two companies involved to 10%.

Conclusion for IM: A small-scale, one-month trial of 5% H_2 blended in an NG pipeline. No operational issues were reported, and the trial was extended to include a 10% H_2/NG blend.

Table 7. Global Hydrogen Blending Projects, according to California Public Utilities Commission (CPUC), as of July 2022[50], where S = Storage, D = Distribution, T = Transmission, E = End Use

CPUC Ref.	Project Name	Project Period	Location	Participants	Keywords	Network Level	Key Topics and Findings	% H_2 Studied	% H_2 Acceptable	Lit. Ref.
1	Hawai'i Gas	1970-Present	U.S.	Hawai'i Gas	Blending Demonstration	T, D	Successful demonstration of long-term blending in NG distribution and transmission pipelines. No available measurement of H_2 leakage or hydrogen-related failure.	10-12	12	44, 45, 46, 47, 48
2	Initial Assessment of the Effects of Hydrogen Blending in Natural Gas on Properties and Operational Safety, Phase 1	2015	U.S. and Canada	Operations Technology Development (OTD) Members, GTI	Materials Integrity Metering	D	Impact of 5% H_2 on non-metallic pipelines was examined. Leakage rate of 5% H_2 blend through elastomer couplings was examined.	5	5	

CPUC Ref.	Project Name	Project Period	Location	Participants	Keywords	Network Level	Key Topics and Findings	% H_2 Studied	% H_2 Acceptable	Lit. Ref.
3	University of California Irvine (UCI), National Fuel Cell Research Center (NFCRC) Campus Hydrogen Microgrid	2016-present	U.S.	UCI NFCRC, NREL, SoCalGas	Blending Demonstration, Leakage, Combustion	D	Odorants are not sufficient to detect leaks. Gas turbines showed a slight drop in total fuel gas flow but no negative impact on emissions overall.	-	-	80, 81
4	M2018-008 Expansion of NYSEARCH RANGE Model & Study of Siloxane Concentration Limits	2019-2020	U.S. and Canada	NYSEARCH members, etaPartners LLC	Blending, End Use	D, E	Results of Wobbe numbers, combustion process, yellow tipping, flame lifting, flame speed, flashback, CO emissions, and NYSEARCH RANGE spreadsheet updated to implement correlation changes developed in the project. An update to the online model is planned.	2-20	10	

CPUC Ref.	Project Name	Project Period	Location	Participants	Keywords	Network Level	Key Topics and Findings	% H_2 Studied	% H_2 Acceptable	Lit. Ref.
5	Enbridge Low-Carbon Energy Project	2021-present	Canada	Enbridge	Blending Demonstration	D, E	An upper limit of 5% H_2 by volume was applicable for the specific Gas Distribution Network. The upper limit for H_2 was found to be 2% based on the local gas composition, heating equipment, and appliances.	0-100	5(D), 2(E)	
6	P2G Ameland	2008-2012	Netherlands	Municipality of Ameland, Joulz, GasTerra, Stein, Kiwa Technology	Domestic Distribution Blending, Metering, End Use Equipment	D	Blending of H_2 up to 20% has no impact on the infrastructure materials and service lines.	20	20	74
7	Underground Sun Storage	2013-2018	Austria	Axiom, Montan Universität, RAG Austria AG (RAG), Energie Institute Verbund	Storage	S	The underground storage facilities are capable of tolerating H_2 content, up to 10%.	10	10	

CPUC Ref.	Project Name	Project Period	Location	Participants	Keywords	Network Level	Key Topics and Findings	% H_2 Studied	% H_2 Acceptable	Lit. Ref.
8	Permeation of Hydrogen Test on Polyamide (Distribution) Pipelines of Different Types of Resins Either PA11 of PA12	2014-2015	Europe	GasNatural, Gaz de France, E.ON Ruhrgas	Integrity, Permeability, Materials	D	The permeation in PA12 resins occurs after less than 24 hours (20 °C and 10 barg). Permeability coefficient ranges from 80 to 100 ml.mm/m^2/bara/day.	100	Not Determined	
9	Energy Storage - Hydrogen injected into the Gas Grid via Electrolysis Field Test - Phase 1	2014-2020	Denmark	Energinet, Evida, Danish Gas Technology Centre, IRD Fuel Cells	Blending Demonstration	S, T, D	The long-term test at the facility was performed with H_2 concentrations of up to 12%.	15	12	
10	GRHYD	2014-present	France	ENGIE, CETIAT, Other Participants	Injection, Blending Demonstration	D	Successful operation up to 20% H_2 injections. The injection was performed for over 5 years.	0-20	20	75, 76

CPUC Ref.	Project Name	Project Period	Location	Participants	Keywords	Network Level	Key Topics and Findings	% H_2 Studied	% H_2 Acceptable	Lit. Ref.
11	ITM Power Thüga Plant	2014-present	Germany	Thüga Group, ITM Power	Blending Demonstration	D	A maximum of 2% H_2 was blended with NG. No compressor was required since the H_2 was produced at the same pressure as the gas distribution network.	2	2	
12	P2G Haßfurt	2016-present	Germany	Next-Kraftwerk	Blending Demonstration	D	The project has been operational since 2016, with positive news stories.	5	5	121, 122
13	Jupiter 1000	2017-present	France	GRTGaz, Atmostat, CEA, McPhy, Leroux et Lotz, Terega	Blending Demonstration	T, D	Not available	0-6	6	
14	HyNTS Aberdeen Vision	2019-present	U.K.	SGN, National Grid, Cadent Energy, Pale Blue Dot Energy, DNV GL	Blending Demonstration	D	No critical obstacles have been identified that would prevent the injection of 2% H_2 into the national transmission system (NTS) at St. Fergus and its distribution through the gas distribution network.	2	2	

CPUC Ref.	Project Name	Project Period	Location	Participants	Keywords	Network Level	Key Topics and Findings	% H_2 Studied	% H_2 Acceptable	Lit. Ref.
15	Wind2Gas Brunsbüttel	2019-present	Germany	Schleswig-Holstein Netz AG, Wind2Gas Energy GmbH, Co. KG, Other participants	Blending Demonstration	T, D	H_2 produced in the wind power-to-gas plant is compressed using two compressors and fed into the high-pressure NG grid at 2%.	2	2	58, 59
16	Snam Contursi Trial	2019-present	Italy	Snam	Blending	D	Italy's gas utility, Snam, began a large-scale experiment in 2019, introducing 5% H_2 into the Italian Gas Transmission Network. In December 2019, Snam doubled the volume of H_2 blend to 10%.	10	10	84

CPUC Ref.	Project Name	Project Period	Location	Participants	Keywords	Network Level	Key Topics and Findings	% H_2 Studied	% H_2 Acceptable	Lit. Ref.
17	Australian Hydrogen Centre	2019-present	Australia	Australian Gas networks (AGN), Department of Energy and Mining (DEM), Department of Environment, Land, Water, and Planning (DELWP), Other Participants	Blending Demonstration	D	The project started to supply H_2 blend of up to 5% renewable H_2 through the existing NG infrastructure.	5	N/A	
18	HyDeploy	2019-present	U.K.	Cadent Gas, Northern Gas Networks, Progressive Energy Ltd., Keele University, Health & Safety Laboratory, ITM Power	Blending Demonstration	D, E	HyDeploy has successfully demonstrated H_2 blending up to 20 mol%. Properly installed and maintained domestic appliances are safe with the blended gas.	20	20	77, 78

7.7 PHMSA Pipeline Incident Reports

PHMSA has maintained a publicly available database of pipeline incidents and failure causes since 1970. Over the years, the reporting regulations and incident report formats have changed. For gas pipelines, data in the following categories are available for download[87]:

- Gas Gathering;
- Gas Transmission;
- Gas Distribution;
- Liquefied Natural Gas;
- Underground Natural Gas Storage; and
- Type R Gas Gathering.

The data from the “Gas Transmission” files were reviewed for the present research. Sixteen (16) incidents related to 100% H_2 were reported, as listed in Table 8. As none of these incidents involved blended H_2/NG, they are not described in further detail in this report.

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Table 8. Incidents on 100% H_2 Transmission Pipelines, as Reported in PHMSA Incident Database[87]

#	Report #	Date	Release	Dia. (in.)	WT (in.)	Grade	Long Seam	Pipe Manufacturer	Install	MAOP (psig)	AG/UG	Failure Type
1	20220025	2/5/2022	Leak	8	0.322	35 ksi SMYS	Seamless	Unknown	1926	375	Underground	Complete weld failure
2	20210022	2/15/2021	Leak	-	-	-	-	-	2017	2,445	Above ground	Erosion
3	20190063	5/5/2019	Leak	10	0.228	API 5L X52	HF-ERW	American Steel Pipe	1992	1,100	Underground	Pinhole
4	20190053	11/12/2018	Leak	10	0.250	API 5L X42	ERW	Unknown	1983	390	Underground	Pinhole
5	20150071	4/28/2015	Leak	-	-	-	-	-	-	1,480	Above ground	Connection failure
6	20080066	6/21/2008	Release	-	-	-	-	-	-	-	Above ground	-
7	20080035	2/28/2008	Rupture	10	0.190	X46	ERW	Unknown	1969	1,000	Underground	Longitudinal tear/crack
8	20070081	7/8/2007	Leak	26	0.310	2030-D	FW	A.O. Smith	1947	900	Underground	Failed butt weld
9	20060140	10/20/2006	Release	-	-	-	-	-	-	1,440	Above ground	-
10	20060042	2/18/2006	Rupture	14	0.250	42 ksi SMYS	FW	A.O. Smith	1929	499	Under Pavement	Circumferential Separation
11	20040029	2/22/2004	Rupture	12	0.220	API 5L X52	ERW	Unknown	1999	1,066	Underground	Longitudinal tear/crack
12	20040018	1/13/2004	Leak	30	0.500	X65	ERW	Berg Steel Pipe Corp.	1991	976	Underground	-
13	20030095	11/2/2003	Rupture	30	0.380	API 5L X52	EFW	A.O. Smith	1957	1,000	Underground	Longitudinal tear/crack
14	20030003	12/3/2002	Rupture	2.5	0.200	135 ksi SMYS	Seamless	Unknown	1962	2,160	Underground	Circumferential Separation
15	20020092	1/16/2002	Rupture	26	0.250	X41	FW	-	-	400	-	Circumferential Separation
16	19850268	1985	Rupture	-	0.220	ASTM A53	-	-	1969	-	Above ground	-

7.8 The IChemE Database (U.K.)

One occurrence of a pipeline incident was found and described in 7.1 HIAD Data.

- IChemE No. 114961997[53] (HIAD Event ID 665) – Release of hydrocarbons from a pipeline.

7.9 HyResource (Australia)

HyResource is a collaborative knowledge-sharing resource supporting the development of Australia's H_2 industry. Its logo is shown in Figure 46.

CSIRO HyResource

Figure 46. HyResource Logo[111]

One occurrence of an H_2 blending project was found and described in Section 7.4.1.1 above.

- IEA Infra. Data Ref. BLE-2 / IEA Prod. Data Ref. 737 – Jemena Green Gas – H2GO Project – Horsley Park, Western Sydney, Australia (2% H_2/NG).

7.10 Other Blending Projects

7.10.1 U.K. – HyNet (2020 - Present) – Convert Infrastructure to 100% H_2 and Blend H_2/NG for Homes and Businesses

HyNet[88] is the commercial realization of H_2 blending into the NG network. HyNet is being developed in collaboration between Cadent and Progressive Energy in northwest England, around Liverpool, Manchester, and Chester. H_2 will be produced from NG at a new plant, and the CO_2 byproduct will be subject to carbon capture and storage (CCS) in depleted oil and gas reservoirs under the seabed.

H_2 will be transported by underground pipelines, just as NG is today. HyNet's H_2 network, being developed by Cadent, is the first of its kind in the U.K. The pipelines will carry 100% H_2 and blend with NG for use in homes and businesses. A diagram of the infrastructure related to HyNet is shown in Figure 47.

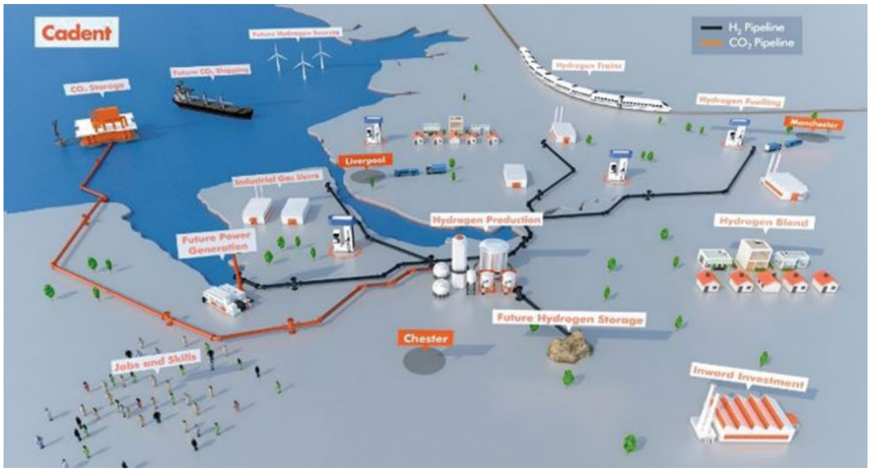

Figure 47. Infrastructure Related to HyNet in the Northwest of England[77]

The strategic objective of HyNet is to build upon the HyDeploy project series to deploy H_2 in homes on a national scale in a non-disruptive manner. By avoiding the need to modify existing domestic appliances, a large barrier to the deployment of H_2 is removed. Once deployed, HyNet will create the foundational infrastructure to facilitate and promote deeper carbon savings via the H_2 vector.

7.10.2 U.S. – SoCalGas and Orange Cove, CA – Blending 0.1 to 5% H_2 in NG (Proposed 2025 - 2028)

In February 2024, Orange Cove's City Council announced[89] that SoCalGas had selected the city for its H_2 blending demonstration project. At the direction of the CPUC, SoCalGas and three other utilities proposed a local demonstration of blending up to 5% renewable H_2 into an NG system serving approximately 10,000 residents and commercial customers in Orange Cove, Fresno County, California. For this project, H_2 will be generated from 1.1 MW of solar panels installed on a 10-acre plot of city land to produce electricity for an electrolyzer to separate hydrogen and oxygen atoms from water.

This project offers a real-world environment to understand better how clean renewable H_2 and NG can be safely delivered to customers in the future. The project will start with small concentrations of 0.1% H_2 and gradually increase to 5% H_2. Active blending is expected to last approximately 18 months in the city. In November 2023, SoCalGas said that if the CPUC approves the project by late 2024, the construction and duration of the project would likely occur between 2025 and 2028.

Currently, the state is looking for a "hydrogen injection standard," or the percentage of H_2 gas that can be blended with the natural gas infrastructure. While utilities have been testing the production of clean H_2 gas and H_2 blending in labs and through smaller-scale projects, a demonstration of H_2 blending in real-world conditions must happen before the CPUC sets the injection standard and the practice is more widely adopted.

The project is not without controversy, as reported by Capital & Main[90]. The small town of Orange Grove is populated by Latino farmworkers, where the average resident makes around $12,000/yr, and the median income is below the federal poverty line. Capital & Main pointed out that in the last two years, suburban residents in Colorado and Oregon rejected H_2 blending efforts. If the project is approved, SoCalGas plans to increase gas rates through 2028 for all California customers by 56 cents per month this year (2024) and 20 cents next year to recover its forecast costs.

Other concerns brought forward include (1) the risks of injecting H_2 into gas lines, which would include an increase in lung-damaging nitrogen oxide pollution inside homes, and (2) that hydrogen can leak easily into the atmosphere and is more explosive than natural gas when exposed to air.

Experts said the low levels of H_2 proposed in Orange Cove, ranging from 1% to 5% of the total fuel volume in the pipeline, probably will not make it much more dangerous than the NG used now. The main concern, critics said, is allowing a group of utilities to use a small, economically distressed town for an experiment they contend will do little to lower climate-altering emissions.

7.10.3 U.S. SoCalGas – [H_2] Innovation Experience - Home in Downey, CA – Blending 20% H_2 in NG (2022 - Present)

SoCalGas describes this project[91,92] as North America's first-ever clean, renewable H_2-powered microgrid and home (see Figure 48). The home demonstrates how net-zero gas made from renewable electricity can be used in pure form or as a blend to fuel energy systems and communities of the future. It features renewable H_2 production and storage, and a nearly 2,000 ft^2 home that can draw power from solar panels and convert excess renewable energy into clean renewable H_2.

All appliances in the home (specifically: tankless water heater, clothes dryer, range top, oven, fireplace, and barbecue) that would normally be powered with NG are instead fueled with a blend of 20% H_2 in NG. Unlike a traditional power utility, a microgrid is a decentralized system that can power a neighborhood instead of an entire city. The microgrid SoCalGas operating in Downey is large enough to support at least 100 homes.

SoCalGas's goal was to show how H_2 can be generated locally from renewable energy and be used in a single Leadership in Energy and Environmental Design (LEED) certified home. The home serves as a demonstration to show the possibilities for wider implementation in California.

Figure 48. [H_2]IE Home in Downey, California[91]

7.10.4 U.S. - Delta, Utah – Conversion of Coal Plant to 30 – 100% H_2/NG Blend

In 1986, Intermountain Power Agency (IPA) opened two coal-fired power plants with a combined capacity of 1,800 MW in Delta, UT. The plants are a major employer in the region, and the local economy relies on its existence. The power is delivered to 35 Utah and Southern California municipal utility partners. Some years ago, Los Angeles, CA, decided only to use coal-free power. As a result, Los Angeles would no longer purchase power from IPP's Delta plant. In response, a plan was made to change the coal-fired plant to a gas-fired plant that can also handle H_2/NG blends and eventually burn 100% H_2.

The Advanced Clean Energy Storage (ACES) Project[93,94] was conceived to produce up to 100 metric tons/day of H_2 from water and renewable energy sources using a 220 MW alkaline electrolyzer bank. By 2025, two advanced H_2-capable power trains (gas turbine units) will be installed as an 840 MW combined cycle power plant. The units can combust a mix of 30% H_2 and 70% NG when they come online in 2025. The gas turbine supplier continues to develop a second-generation combustion system to enable the units to achieve 100% H_2 fueling by 2045.

ACES will take advantage of Delta's geographic location over two gigantic solution-mined caverns sited in the only salt dome in the Western U.S. to store H_2 gas with a combined 300 GWh of energy (see Figure 49). When there is an oversupply of solar and wind power, the H_2 produced from that excess electricity can be stored and used again to produce electricity when needed.

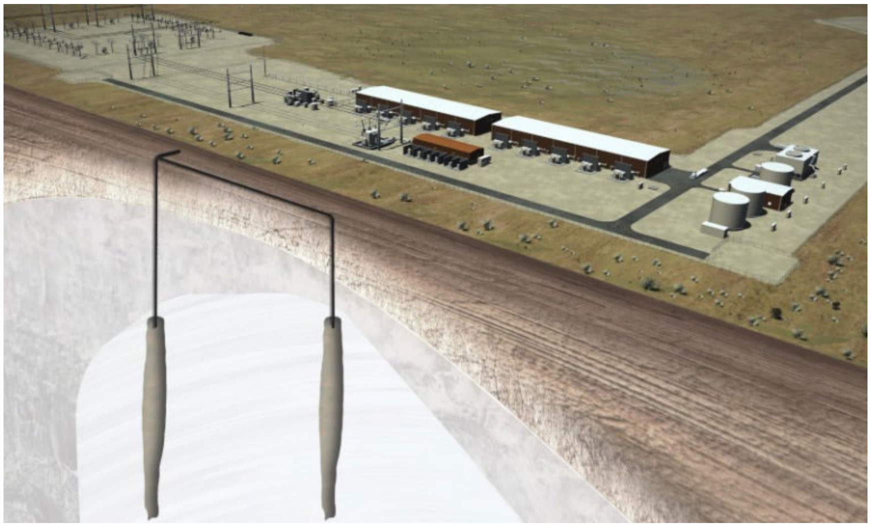

Figure 49. Rendering of Advanced Clean Energy Storage Salt Caverns[83]

7.10.5 U.S. – Department of Energy - H2@Scale (2016 - Present)

Since 2016, H2@Scale has been a DOE initiative[95] to bring together stakeholders for H_2 production, transport, storage, and utilization. It includes DOE-funded projects and national laboratory-industry co-funded activities to accelerate the early-state research, development, and demonstration of applicable H_2 technologies. Most recently, in October 2024, DOE announced nine cooperative projects that will complement existing H2@Scale efforts and support DOE's Hydrogen Shot™ goal(7). The logo of H2@Scale is shown in Figure 50.

H2@Scale℠
U.S. Department of Energy

Figure 50. Logo of H2@Scale

DOE's Office of Energy Efficiency and Renewable Energy (EERE) and DOE's HFCT office focus on R&D areas[96] such as:

- H_2 performance analysis and operations;
- H_2 distribution component development;

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[7] Hydrogen Shot™ aims to reduce the cost of clean hydrogen to $1 per kilogram by 2031.

- Advanced H_2 production concepts; and
- H_2 integration with energy generation.

Thus far, the H2@Scale effort does not appear to have placed much emphasis on the transportation of H_2 by pipeline, nor on the effects that inserting H_2/NG blends may have on the mechanical integrity of pipeline systems.

Like its 2020 version of the Hydrogen Program Plan[97], DOE's 2024 updated Hydrogen Program Plan[98] mentions the R&D for blending H_2 into existing pipelines commingled with NG, "city gas", or other products. Related to H_2 blending, both plans also highlight the progress for large-frame turbines that can fire H_2/NG blends for power generation:

- Simple-cycle turbines or aero-derivative machines:
    - Materials available for 90% H_2/NG blends; and
    - Currently available (2024) commercial equipment for 90% H_2/NG blends.
- Combined-cycle turbines:
    - Materials available for 50% H_2/NG blends; and
    - Currently available (2024) commercial equipment for 30% H_2/NG blends.

7.10.6 Romania - Transgaz Pilot Project "RO-HY" for H_2 Injection in NG Pipelines (Unspecified % H_2/NG)

- In November 2021, a film made by Transgaz presented the start of the company's two-year research pilot project, RO-HY (Romania Hydrogen), for H_2 injection in NG transmission and distribution pipelines in Romania[99,100].
- This experimental independent study aims to establish:
    - % H_2 blend that can be safely transmitted through the current transmission infrastructure;
    - The main vulnerabilities of the system in the context of using this blend;
    - How to manage these vulnerabilities; and
    - Implications that H_2 addition has on the final consumers.
- The project's main objective is to evaluate the effect of the H_2/NG blend on the performance under operating conditions of the main equipment and technical solutions used in the NTS.

- At the same time, the pilot installation can determine the impact of the H_2/NG blend on a gas distribution network up to the final consumer.

- Features of the test equipment include:
    - The experimental facilities are outdoors, on a concrete platform, and protected by a metal cover.
    - The facility allows for H_2 to be injected into the gas flow in a controlled manner and offers multiple possibilities for observing and recording the effects it has on the flow and the behavior of the fluid, as well as the impact of the blend on the materials and equipment analyzed, including the facilities used and the environment.
    - Configuration of the installation allows for different flow scenarios to be carried out, which can be monitored through the gas measurement and analysis equipment.
    - Modular construction allows for interposing various equipment that can thus be tested in real field testing conditions.
    - Installation has a test chamber that allows samples to be exposed to the conditions inside the installation. At the end of the exposure period, the effect that the H_2/NG blending has on them is obtained by reference to the state of the control samples.

- *This project is operational, involves an unspecified H_2/NG blend, and has a test setup that includes small-scale transmission and distribution pipeline components and piping.*

Figure 51. H_2 Blending Equipment of RO-HY Project by Transgaz, in Romania[99]

8 CONCLUSIONS

The following conclusions were formulated based on the results from this Task 5 review.

1. Laboratory testing shows that exposure to H_2-blended NG has a detrimental effect on the material properties of pipeline steels. The extent to which these effects affect pipeline integrity has not been fully studied, particularly for high-stress pipelines.
    a. The material properties affected include (1) reduced fracture toughness, (2) increased fatigue crack growth rate, da/dN, and (3) increased corrosion fatigue rate, da/dt.
    b. The deteriorated material properties can have two distinct effects on the remaining life of existing anomalies in blended H_2/NG compared to NG:
        i. Reduced fracture toughness can cause a smaller-size anomaly to fail; and
        ii. Increased da/dN and/or da/dt can cause a shorter time to reach an anomaly's critical dimensions for failure.
    c. The material property degradation severity from hydrogen embrittlement depends on the absorbed H-concentration in the steel:
        i. It depends on the partial pressure of H_2;
        ii. It can occur at concentrations as low as 1% H_2;
        iii. It can be mitigated by other gases, such as CO_2, CO, O_2, or water; and
        iv. It depends on the pipeline steel being tested. Steel with higher hardness and/or higher strength grade is more susceptible.
2. No lower bound has been established in laboratory testing where H_2 blending has been found not to have a detrimental effect on material properties.
    a. There is no distinct blend percentage H_2/NG at which a pipeline system can be assessed as a 100% NG system, a 100% H_2 system, or something in between.
    b. In the absence of this distinction, the safest practice is to assume material properties based on exposure to 100% H_2 gas; and
    c. Steel from each pipeline considered to transport H_2 should be tested individually to establish its properties in H_2.
3. Global practical experience with blended H_2/NG of different concentrations shows that using H_2-blended gas is feasible and that the detrimental effects of H_2 on steel may not greatly impact pipeline integrity. This experience is based on low-stress and distribution

pipelines. More experience needs to be established with H_2 blending on high-stress pipelines. However, the fatigue life of defects in pipelines carrying H_2/NG may be shorter than for NG alone, warranting a shorter reinspection interval for those pipelines.

   a. The reasons for the low impact are:

      i. Low pipeline operating pressures (low stresses in the pipeline);

      ii. Small pressure fluctuations (gas pipelines generally have less cyclic pressure than liquid pipelines);

      iii. Deteriorated material properties only have adverse effects in areas where defects/anomalies are present; and

      iv. Small anomalies are not at high risk of initiating cracks; therefore, an increase in CGR is not applicable (cracks do not grow at all).

4. Based on a review of databases and other sources with information on H_2-related incidents and accidents, H_2 production and distribution pilot projects, blending facilities, and pipelines to transport H_2-containing gas blends, there were no counter-indications toward the successful use of H_2/NG blending. However, most project descriptions provided little technical information.

   a. There are zero reported failures related to hydrogen embrittlement for pipelines carrying blended H_2/NG.

   b. There is a long successful history of using towngas in Singapore (150+ years, up to 50% H_2 in NG), Hong Kong Singapore (150+ years, up to 50% H_2 in SNG), and Hawai'i (50+ years, up to 15% H_2 in SNG).

   c. Globally, dozens of small-scale and pilot projects demonstrate the successful use of different H_2/NG blends in gas distribution networks, with pipes up to 8 inches in diameter.

      i. Most projects do not publish the pipeline diameters, wall thicknesses, steel grades, maximum operating pressures, or pressure cycling data;

      ii. Some projects use polyethylene piping networks; and

      iii. Detailed integrity management data is generally not published. Instead, the public-facing information usually focuses on system safety, cost to the consumer, environmental benefits, and the safe use of home appliances.

   d. The pilot projects use a variety of sources for the H_2 blends: green sources such as wind, solar, water, and nuclear power, and gray and blue (with carbon capture and storage) sources, such as steam methane reforming using naphtha or NG.

5. In the absence of shared integrity management, component performance, and material property data from operators who have run pilot or small-scale projects with blended H_2/NG systems, it is not possible to reliably estimate the remaining life of such systems with postulated or known flaws.
    a. At present, fracture mechanics and remaining life modeling are limited because only laboratory material property testing data are publicly available.

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9 APPENDIX A – HIAD AND ARIA CASE DESCRIPTIONS INVOLVING H_2, BUT NOT APPLICABLE TO BLENDED H_2 PIPELINES

9.1 HIAD Event ID 1057 (PHMSA Report No. 36436) - Release and fire from an H_2 pipeline

- Also refer to PHMSA Report No. 364636[101].

- On July 3, 2022, a fire occurred on a 100% H_2 underground transmission pipeline in the U.S. The pipeline was 8 inches nominal diameter, 0.322 inches wall thickness, and was made of seamless Grade B (specified minimum yield strength (SMYS) of 35 ksi) line pipe. The pipeline was originally installed in 1926. The pressure at the time of the incident was 338 psig (13% of SMYS). The MOP of this pipeline was 375 psig (14% of SMYS).

- The leak was detected when the operation control center (OCC) recognized that customer flow and pressure had dropped significantly. An upstream (U/S) remotely operated valve was closed, and a technician confirmed the breach in the pipeline. Isolation was achieved by closing the incident site's manual block valves U/S and downstream (D/S).

- The initial cause was the complete failure of a pipe girth weld, probably at the HAZ, by hydrogen-induced cracking. The HIAD database lists the failure causes as "system design error," "material/manufacturing error," "installation error," and "management factors."

- *A leak occurred on a 100% H_2 transmission pipeline: The direct cause was hydrogen-induced cracking (HIC) of a girth weld.*

9.2 HIAD Event 478 – H_2 release from an H_2 pipeline

- On May 6, 2020, a leak without ignition occurred on a 100% H_2 pipeline in Belgium[102]. A resident who heard an abnormal noise while walking his dog found the leak around midnight. The pipeline was depressurized within an hour. The pipeline was completely emptied and purged with N_2. The pipeline was repaired the next day. The cause of the failure was attributed to corrosion of the pipeline and was probably associated with a lack of maintenance. The HIAD database lists the failure causes as "material/manufacturing error," "job factors," and "management factors."

- *A leak occurred on a 100% H_2 transmission pipeline: The direct cause of the leak was corrosion.*

9.3 HIAD Event ID 759 – Fire from an H_2 pipeline

- On October 12, 2007, a fire broke out along a "transition corridor" combining several underground pipelines transporting hazardous substances, including 100% H_2, kerosene, and ethylene oxide in the Netherlands[103]. The fire was brought under control within a few minutes due to the limited size of the leak.

- According to the appropriate inspectorate, welding work performed nearby ignited an H_2 leak on an underground pipeline. Differential ground settlement with local deformation of the pipeline at the level of a CP system caused the H_2 leak. The sandy soil facilitated this settlement due to heavy equipment on the ground surface used for earthworks to lay a new kerosene pipe.

- The leakage was caused by a mix of several tension factors executed on the H_2 pipeline. The predominant stress factor was the gradual settlement of the pipeline and the earth surrounding it. The settlement took place over several years and resulted in the pipeline bending at a spot where the pipeline got stuck on a fixed structure (a feed-through in which the pipeline enters a building.) The bending forces caused tensions on the CP coupling nearby in the pipeline, which eventually started to leak. Other stressing factors that might have contributed to the accident were unallowed heavy traffic and the placement of heavy equipment on the soil covering the pipeline.

- The HIAD database lists the failure causes as "installation error" and "management factors."

- *A leak occurred on a 100% H_2 transmission pipeline: The direct cause of the leak was ground settlement.*

9.4 HIAD Event ID 891 (ARIA No. 53345[104]) and HIAD Event ID 1027 (ARIA No. 57406[105]) - Fire from an H_2 pipeline damaged by excavation works

- On March 21, 2019, a fire and explosion occurred on a 100% H_2 pipeline in Braine-Le-Comte, Belgium. Excavation work was performed near a buried pipeline of gaseous H_2. An excavation machine used for agricultural work hit the pipeline, causing an under-expanded jet fire. The machine was burnt during the accident (see Figure 52).

- The immediate cause was the mechanical damage to an underground H_2 pipeline. The specific root cause was not identified in the database but is likely related to the failure to properly inform the excavating company of the presence of the pipeline.

- *A leak occurred on a 100% H_2 transmission pipeline: The direct cause of the leak was mechanical damage.*

Figure 52. Screen Capture of Video Showing Fire After H_2 Pipeline was Hit by an Excavator

9.5 HIAD Event ID 933 (ARIA No. 43705) – Release from an H_2 pipeline

- On April 18, 2013, a leak without ignition occurred on a 100% H_2 pipeline in Guarbecque, France[106]. During maintenance work on a gas pipeline (3-inch diameter (DN 80), 1,088 psig (75 bar)) carrying H_2, a worker heard a leak. The operator measured a concentration of 3% of the low flammability limit at a few centimeters from the leak and no detection beyond 25 cm. The area was highly ventilated. The technicians secured the area, isolated the section five hours later, and started the controlled gas release. After two additional hours, the pressure had reduced to zero, and they started flushing the pipeline with inert N_2 gas. The pipe, which was originally installed in 1988, was repaired the next day. The HIAD database lists the failure cause as "unknown."

- *A leak occurred on a 100% H_2 transmission pipeline: The direct cause of the leak was unknown.*

9.6 HIAD Event ID 1058 (PHMSA Report No. 20190063) – Leak from an H_2 pipeline

- On May 5, 2019, a third party notified a pipeline operator that there was a possible leak on its 100% H_2 underground pipeline in the U.S. The pipeline was 10 inches in nominal diameter, 0.228 inches wall thickness, and made of API 5L Grade X52 line pipe with an ERW long-seam weld. The pipeline was originally installed in 1992. The pressure at the time of the incident was 800 psig (35% of SMYS). The MOP of this pipeline was 1100 psig (50% of SMYS).

- The leak was identified by sound. No ignition took place with this release. Operator personnel confirmed that H_2 was present in the area, manual isolation valves were shut to close in the segment, and the pipeline was manually blown down. There was no immediately recognizable cause of the incident. No excavators were operating in the area, and CP testing showed no abnormalities. The suspected area of the leak was excavated, but the pipe was shown to be in excellent condition. Upon further investigation, it was determined that the leak was most likely located underneath a small, non-navigable drainage canal. Unable to excavate under the water, a new pipe was installed, rerouting around the leak.

- Further investigation showed that the immediate cause of the damage that caused the leak was probably a lightning discharge through a rod passing in the vicinity of the pipeline. The inactive segment of the pipe where the leak was found was further investigated with a tethered ILI tool to further investigate the cause of the leak. Results showed an anomaly near a grounding rod for a nearby electrical transmission tower.

- An additional direct current voltage gradient (DCVG) inspection showed a similar anomaly, correlating the results of the ILI. It is, therefore, suspected that lightning struck the tower during a storm, creating a surge of energy that was released into the ground through the grounding rod. This electrical energy created an anomaly on the pipe, which eventually led to a small leak (pinhole leak). The HIAD database lists the failure cause as an "installation error."

- *A leak occurred on a 100% H_2 transmission pipeline: The direct cause of the leak was a lightning strike.*

9.7 HIAD Event ID 1059 (PHMSA Report No. 20190053) - Leak from an H_2 pipeline

- On November 12, 2018, a leak without ignition occurred in a 100% H_2 underground pipeline in the U.S. The pipeline had a nominal diameter of 10 inches and 0.250 inches wall thickness. It was made of API 5L Grade X42 line pipe with an ERW long-seam weld. The pipeline was originally installed in 1983. The pressure at the time of the incident was 260 psig (13% of SMYS). The MOP of this pipeline was 390 psig (20% of SMYS).

- The leak was discovered due to bubbling water in the ditch. No visible hydrocarbon sheen was noted, indicating a probable non-hydrocarbon gas leak. Different pipelines in the area were tested, and the source of the leak was found. The Supervisory Control and Data Acquisition (SCADA) system was functional and operating under normal conditions at the time of the incident. The pipeline pressure drop due to the failure was so small that it was not indicated on the Control Room SCADA screen.

- The pipeline was depressurized to the point where the bubbling stopped. The leak released 1.7 mmscf (approx. 4 tons) of H_2 to the atmosphere. ILI was performed, and five areas of concern were found, all on the bottom of the pipe and in low-lying areas. The rerouting of the affected section lasted more than six months, and the repair was expected after one year.

- The pipeline section was in water. The loss of containment has been attributed to internal corrosion of pipeline materials. The difficulty in accessing the location of the release could hint at a shortcoming in the pipeline's design or an error in the installation.

- The HIAD database lists the failure causes as "material/manufacturing error," "installation error," and "management factors."

- *A leak occurred on a 100% H_2 transmission pipeline: The direct cause of the leak was metal loss from internal corrosion.*

9.8 HIAD Event ID 122 – Explosion

- On September 14, 2007, an explosion occurred in the compression room of a methanol synthesis manufacturer in Azot, Severodonetsk, Ukraine. The original source reference of the HIAD database was lost. The record describes that because of pipeline destruction, a mixture of pressurized gases (mostly H_2) filled the compression room and then exploded. The HIAD database lists the failure causes as "material/manufacturing error" and "management factors." A specific reason for the pipeline destruction was not listed.

- *Does not apply to transmission pipelines: This incident occurred in a methanol plant. It involved a gas blend, mostly H_2.*

9.9 HIAD Event ID 1045 – Pressure vessel failure

- On June 28, 2015, a pressure vessel leaked and exploded in China[107]. The vessel affected by the incident was a gas storage used for desulphurization. The desulphurization gas had a high H_2 content. The vessel had cracks in the upper transverse fillet welds at the gas inlet, which caused low-stress brittle fractures. The cracks had been found during maintenance but were not fixed, eventually causing a gas release.

- Approximately 2.5 hours after a leak was detected and reported, the first explosion occurred. As the heat exchanger explosion faced the desulphurization pump room, the leaking desulphurization gas gathered in the pump room under the effect of the first explosion flame. Seven seconds later, a second explosion occurred in the desulphurization pump room, resulting in three deaths. Due to the impact of debris from the first explosion and the high temperature of the open flame, a third explosion occurred in another cracked pressure pipe.

- The immediate cause was corrosion of a welded joint with a low brittle fracture resistance. One of the root causes was identified as a lack of maintenance and repair. The HIAD database lists the failure causes as "material/manufacturing error," "job factors," and "management factors."

- *Does not apply to transmission pipelines: This incident occurred in a chemical plant. The incident did involve a gas blend with high H_2 content.*

9.10 HIAD Event ID 1048 - Leakage and ignition of hydrocarbon mixture from a pipeline

- On July 22, 2021, a mixture of mainly CO and H_2 was released from a pipeline transferring process gases in a not further specified unit of a chemical plant in China. The flammable mixture ignited, possibly due to static electricity, and the failure resulted in 22 deaths and eight injuries. The HIAD database lists the failure cause as "unknown."

- *Does not apply to transmission pipelines: This incident occurred in a chemical plant and involved a gas blend of CO and H_2.*

9.11 HIAD Event ID 83 – Explosion and fire in a desulphurization unit of a refinery

- On June 3, 2007, an 8-inch diameter heat-insulated carbon steel pipeline ruptured at the desulphurization unit of a refinery in France. The pipeline carried a hydrocarbon/H_2 mixture and was located on an upper rack within the refinery. At the time of the incident, the desulphurization unit was shut down for scheduled cleaning of a cooling tower with reintroduction of a gas mixture into the system at a high H_2 content.

- The event triggered an explosion whose pressure surge was evaluated by the site operator at approximately 0.87 psig (60 mbar) at 33 feet (10 m). Since the leak was being fueled, the fire affected other pipelines and the exhaust valves connected to the flare system. This explains the persistence of several secondary fire outbreaks, finally extinguished eight hours later. The operator estimated the quantities released to be less than 2 tons of liquid hydrocarbons and 50 kg of H_2.

- The rupture was due to external corrosion localized on the pipeline supporting structure. Over a section approximately 18 inches (45 cm) long on the line's lower half-circumference, the residual pipeline thickness equaled 0.118 inches (3 mm) on average versus 0.256 inches (6.5 mm) originally and eventually reached 0.008 inches (1.2 mm) in certain zones. The rupture occurred in two stages: an initial break, followed by propagation of the opening due to the high pressure of gases circulating inside the pipeline.

- The HIAD database lists the failure causes as "material/manufacturing error" and "management factors."

- *Does not apply to transmission pipelines: This incident occurred in a chemical plant. The incident did involve a gas blend of hydrocarbons and H_2.*

9.12 HIAD Event ID 11 – H_2 fire from a pipeline

- On April 10, 1989, a fire occurred at a refinery in Richmond, California, USA[108]. A 2-inch diameter line carrying 100% H_2 gas at approximately 2,800 psig (approximately 19.3 MPa) failed at a weld, resulting in a high-pressure H_2 fire. The fire resulted in flame impingement on the support of a 100-ft-high reactor in a hydrocracker unit. The steel skirt for this reactor, which was 10 to 12 ft in diameter and had a wall thickness of 7 inches, subsequently failed. The collapse of this reactor damaged fin-fan coolers and other processing equipment, greatly increasing the size of the loss. It is believed that the hydrocracker unit was being shut down for maintenance at the time of the loss. The reactor was in an H_2 purge cycle. The cause of the initial H_2 leak is believed to have resulted from the failure of an elbow-to-reducer weld in the 2-inch H_2 preheat exchanger bypass line. The HIAD database lists the failure cause as a "system design error."

- *Does not apply to transmission pipelines: This incident occurred on a 2-inch diameter H_2 process piping at a refinery.*

9.13 HIAD Event ID 135 - Fire on a hydrogen pipeline in a metallurgy plant

- On November 30, 2005, a 100% H_2 line running to a furnace caught fire at a metals plant in the U.S. The HIAD database's original source reference was lost.

- *Does not apply to transmission pipelines: This incident occurred in a metals plant.*

9.14 HIAD Event ID 578 – Fire at a refinery

- On April 12, 1985, a leak and ignition occurred in an H_2 and catalyst loading line of a heavy oil unit at a refinery in Saudi Arabia. The most likely cause was that an H_2 purge pipeline failure allowed H_2 to escape. The leaked gas mixed with hot oil, bringing the temperature to approximately 825 °F (441 °C), i.e., above the auto-ignition temperature. The HIAD database lists the failure cause as a "material/manufacturing error."

- *Does not apply to transmission pipelines: This incident occurred on a process line at a refinery.*

9.15 HIAD Event ID 165 – Release from a pipeline in a refinery

- On January 2, 2008, a 100% H_2 feed line ruptured without ignition at an oil refinery in Germany. No cause was provided. The HIAD database lists the failure cause as a "material/manufacturing error."

- *Does not apply to transmission pipelines: This incident occurred on a process line at a refinery.*

9.16 HIAD Event ID 114 (ARIA No. 10347[109]) – Fire in the desulphurization unit of a refinery

- On October 20, 1995, a pipeline failed at a desulphurization unit of a refinery in Gelsenkirchen, Germany. The pipeline operated at 725 psig (50 bar) to recycle H_2 (containing H_2S impurities). The pipe failed due to corrosion, and the released H_2 ignited. The unit contained 4,000 kg of H_2, but it is unknown if all of it was released. The unit was stopped, depressurized, and put under N_2.

- The immediate cause was the failure of an H_2 pipe due to corrosion. The accident investigation discovered that the part of the 4-inch (100 mm) diameter pipe that failed had a residual thickness of 0.078 inch (2 mm) instead of the nominal 0.250 inch (6.3 mm). The ARIA report does not mention any root cause, but judging by the deep corrosion, a lack of adequate inspection/maintenance can be postulated. The HIAD database lists the failure causes as "material/manufacturing error" and "management factors."

- *Does not apply to transmission pipelines: This incident occurred on a 4-inch diameter process line at a refinery.*

9.17 HIAD Event ID 622 – Release of H_2

- On July 14, 1974, a release of H_2 occurred at a chemical plant in the U.S. H_2 escaped from a leak in a pipeline connection to a cylinder. The original source of information was lost, and no cause was provided. The HIAD database lists the failure causes as "job factors" and "management factors."

- *Does not apply to transmission pipelines: This incident occurred in a chemical plant.*

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Table 9. List of Hydrogen Pipeline Incidents, Selected from Records of HIAD 2.1 Database[51]

Pipeline Type	HIAD ID	Title	Initiating System	Physical Effects	Consequences	Country	Date
Hydrogen Pipeline	**11**	**H_2 fire from a pipeline**	H_2 system initiating event	H_2 release and ignition	Fire	UNITED STATES	1989-04-10
Hydrogen Tank Venting Line	**58**	**Liquid H_2 release from a rail tanker**	H_2 system initiating event	Unignited H_2 Release	Leak no ignition	ITALY	1991-07-09
Hydrogen-Hydrocarbons Blended Pipeline	**83**	**Explosion and fire in a desulphurization unit of a refinery**	H_2 system initiating event	H_2 release and ignition	Explosion	FRANCE	2007-06-03
Coke Oven Gas Pipe Flange	**84**	**Explosion in a foundry**	H_2 system initiating event	H_2 release and ignition	Explosion	BELGIUM	2002-10-22
Chlorine Pipeline with Hydrogen Impurities	**104**	**Explosion in an electrolyzer for chlorine production**	H_2 system initiating event	H_2 release and ignition	Explosion	FRANCE	2005-09-05
Hydrogen Pipeline with Sulfide Impurities	**114**	**Fire in the desulphurization unit of a refinery**	H_2 system initiating event	H_2 release and ignition	Explosion	GERMANY	1995-10-20
Hydrogen Blended Pipeline	**122**	**Explosion**	H_2 system initiating event	H_2 release and ignition	Explosion	UKRAINE	2007-09-14
Hydrogen Pipeline	**135**	**Fire on a H_2 pipeline in a metallurgy plant**	H_2 system initiating event	H_2 release and ignition	Fire	UNITED STATES	2005-11-30
Chlorine Pipeline with Hydrogen Impurities	**151**	**Fire at a chlorine electrolyzer plant**	H_2 system initiating event	Unignited H_2 Release	Leak no ignition	FRANCE	2004-01-13
Hydrogen Pipeline	**165**	**Release from a pipeline in a refinery**	H_2 system initiating event	Unignited H_2 Release	Leak no ignition	GERMANY	2008-01-02
Hydrogen Piping Flange Bolts	**175**	**Bolts rupture due to hydrogen embrittlement**	H_2 system initiating event	No H_2 Release	Near miss	SPAIN	2003-12-01
Hydrogen-Nitrogen-Ammonia Blended Piping	**194**	**Explosion in an ammonia plant**	H_2 system initiating event	H_2 release and ignition	Explosion	FRANCE	2000-09-14
Hydrogen Pipeline	**198**	**Fire in a refinery**	Non-H_2 system initiating event	H_2 release and ignition	Fire	UNITED STATES	2000-06-30

Pipeline Type	HIAD ID	Title	Initiating System	Physical Effects	Consequences	Country	Date
Hydrogen-Nitrogen-Methane-Carbon Dioxide-Water Blended Piping	**208**	**Fire in a refinery**	H_2 system initiating event	H_2 release and ignition	Explosion	EUROPEAN UNION	1987-12-23
Hydrogen Piping	**268**	**Explosion in a refinery**	H_2 system initiating event	H_2 release and ignition	Explosion	SOUTH KOREA	1991-02-14
Hydrogen Flange	**345**	**Fire from a H_2 pipeline under maintenance**	H_2 system initiating event	H_2 release and ignition	Fire	FINLAND	2003-06-16
Biogas-Water Blended Pipeline	**461**	**Emergency stop of CHP plant**	Non-H_2 system initiating event	No H_2 Release	Near miss	ITALY	2017-12-17
Hydrogen Pipeline	**478**	**H_2 release from a H_2 pipeline**	H_2 system initiating event	Unignited H_2 Release	Leak no ignition	BELGIUM	2019-05-06
Hydrogen Pipeline	**578**	**Fire at a refinery**	H_2 system initiating event	H_2 release and ignition	Fire	SAUDI ARABIA	1985-07-12
Hydrogen Pipeline	**582**	**Explosion on a H_2 compressor**	Non-H_2 system initiating event	H_2 release and ignition	Explosion	UNITED STATES	1985-12-06
Vinyl Chloride Pipeline	**606**	**Fire during the production of CVD coating**	H_2 system initiating event	H_2 release and ignition	Fire	JAPAN	1991-10-30
Hydrogen Piping	**620**	**Explosion at the catalytic reformer unit of a refinery**	Non-H_2 system initiating event	H_2 release and ignition	Explosion	UNITED STATES	1974-11-14
Hydrogen Pipeline	**622**	**Release of H_2**	H_2 system initiating event	Unignited H_2 Release	Leak no ignition	UNITED KINGDOM	1974-07-14
Chlorine Pipeline with Hydrogen Impurities	**634**	**Explosion in the chlorine line of a sodium hydroxide electrolysis unit**	H_2 system initiating event	H_2 release and ignition	Explosion	JAPAN	1985-05-18
Hydrogen-Additives Blended Pipeline	**636**	**Fire - H_2**	H_2 system initiating event	H_2 release and ignition	Fire	JAPAN	1985-02-14
Hydrogen-Naphtha Blended Piping	**651**	**Fire - other agent**	H_2 system initiating event	H_2 release and ignition	Explosion	UNITED KINGDOM	1971-01-01

Pipeline Type	HIAD ID	Title	Initiating System	Physical Effects	Consequences	Country	Date
Hydrogen-Hydrocarbons Blended Pipeline	**665**	**Release of hydrocarbons from a pipeline**	H_2 system initiating event	H_2 release and ignition	Explosion		1997-01-01
Hydrogen Pipeline	**759**	**Fire from a H_2pipeline**	H_2 system initiating event	H_2 release and ignition	Fire	NETHERLANDS	2007-10-12
Hydrogen Piping	**783**	**Fire in the hydrogenation reactor of an alcohol and acids production plant**	Non-H_2 system initiating event	H_2 release and ignition	Fire	FRANCE	2001-10-08
Hydrogen-Nitrogen Blended Piping	**796**	**Fire in an NH_3 production plant**	H_2 system initiating event	H_2 release and ignition	Fire	BELGIUM	2014-01-14
Hydrogen Piping	**807**	**Leakage in an NH_3 and fertilizer plant**	H_2 system initiating event	Unignited H_2 Release	Leak no ignition	FRANCE	2018-07-24
Hydrogen Piping	**840**	**Release from an H_2 line to the desulphurization unit of a refinery**	Non-H_2 system initiating event	No H_2 Release	Leak no ignition	FRANCE	2006-04-01
Hydrogen Flange	**884**	**Explosion in the storage of an HRS**	H_2 system initiating event	H_2 release and ignition	Explosion	NORWAY	2019-06-10
Hydrogen Pipeline	**891**	**Fire from an H_2 pipeline damaged by excavation works**	H_2 system initiating event	H_2 release and ignition	Fire	BELGIUM	2019-03-21
Hot Oil Pipeline	**902**	**H_2 fire in the hydro-desulphurization unit of a refinery**	Non-H_2 system initiating event	H_2 release and ignition	Explosion	VENEZUELA	1984-12-13
Piping Joint	**922**	**H_2 fire from a gas pipeline in a nuclear power plant**	H_2 system initiating event	H_2 release and ignition	Fire	FRANCE	2017-08-09
Hydrogen Pipeline	**933**	**Release from a H_2 pipeline**	H_2 system initiating event	Unignited H_2 Release	Leak no ignition	FRANCE	2013-04-18

Pipeline Type	HIAD ID	Title	Initiating System	Physical Effects	Consequences	Country	Date
Hydrogen-Diesel-Hydrogen Sulfide Blended Piping	**947**	**Release of light hydrocarbons in a refinery**	Non-H_2 system initiating event	Unignited H_2 Release	Leak no ignition	FRANCE	2011-04-28
Hydrogen-Methane-Nitrogen Blended Piping	**952**	**H_2 leak at a refinery**	H_2 system initiating event	United H_2 Release	Leak no ignition	FRANCE	2010-02-15
Hydrogen Piping	**958**	**H_2 fire in a refinery**	H_2 system initiating event	H_2 release and ignition	Fire	FRANCE	2007-10-01
Hydrogen-Methane-Ethane Blended Piping	**959**	**Explosion and fire in a chemical plant producing aromatic hydrocarbon**	H_2 system initiating event	H_2 release and ignition	Explosion	GERMANY	2007-07-10
Hydrogen-Hydrogen Sulfide-Water-Hydrocarbon Piping	**965**	**Release of H_2 and H_2S in a refinery**	H_2 system initiating event	Unignited H_2 Release	Leak no ignition	FRANCE	1998-10-10
Hydrogen-Methane-Hydrocarbons Piping	**969**	**H_2 explosion at a refinery**	H_2 system initiating event	H_2 release and ignition	Explosion	UNITED STATES	2009-11-04
Hydrogen Piping	**973**	**Explosion and fire at a metal powder metallurgy plant.**	H_2 system initiating event	H_2 release and ignition	Explosion	UNITED STATES	2011-05-27
Water Sprinkler Piping	**1012**	**Accidental formation and ignition of H_2 due to corrosion**	Non-H_2 system initiating event	H_2 release and ignition	Fire	FINLAND	2020-06-29
Hydrogen Pipeline	**1027**	**Explosion of a H_2pipeline**	H_2 system initiating event	H_2 release and ignition	Explosion	BELGIUM	2021-03-21
Hydrogen-Naphtha Blended Piping	**1042**	**Explosion of a flammable mixture in a petrochemical plant**	H_2 system initiating event	H_2 release and ignition	Explosion	PEOPLE REPUBLIC OF CHINA	2020-01-14
Hydrogen Gas-Chemicals Blended Vessel	**1045**	**Pressure vessel failure in a chemical plant**	H_2 system initiating event	H_2 release and ignition	Explosion	PEOPLE REPUBLIC OF CHINA	2015-06-28
Hydrogen Valve	**1046**	**Explosion at the hydrogenation tower of a refinery**	H_2 system initiating event	H_2 release and ignition	Explosion	PEOPLE REPUBLIC OF CHINA	2015-03-18

Pipeline Type	HIAD ID	Title	Initiating System	Physical Effects	Consequences	Country	Date
Hydrogen-Blended Piping	**1047**	**Explosion at a methanation reactor**	H_2 system initiating event	H_2 release and ignition	Explosion	PEOPLE REPUBLIC OF CHINA	2011-04-23
Hydrogen-Carbon Monoxide Blended Pipeline	**1048**	**Leakage and ignition of hydrocarbon mixture from a pipeline**	H_2 system initiating event	H_2 release and ignition	Explosion	PEOPLE REPUBLIC OF CHINA	2021-07-22
Hydrogen-Nitrogen-Methane Blended Pipeline	**1049**	**Explosion at a pipeline of a petrochemical plant**	H_2 system initiating event	H_2 release and ignition	Explosion	PEOPLE REPUBLIC OF CHINA	2003-03-13
Hydrogen Pipeline	**1057**	**Release and fire from a H_2 pipeline**	H_2 system initiating event	H_2 release and ignition	Fire	UNITED STATES	2022-03-07
Hydrogen Pipeline	**1058**	**Release and fire from a H_2 pipeline**	H_2 system initiating event	Unignited H_2 Release	Near miss	UNITED STATES	2019-05-05
Hydrogen Pipeline	**1059**	**Release and fire from a H_2 pipeline**	H_2 system initiating event	Unignited H_2 Release	Near miss	UNITED STATES	2018-11-12
Hydrogen Flange	**1060**	**Release and fire from a H_2pipeline**	H_2 system initiating event	H_2 release and ignition	Fire	UNITED STATES	2015-04-28
Hydrogen-Cyclodecane Blended Piping Manifold	**1067**	**Fire in a chemical factory**	H_2 system initiating event	H_2 release and ignition	Fire	FRANCE	2022-03-01
Hydrogen-Methane Blended Pipeline	**1085**	**H_2/CH_4 release at a gas booster of a pipeline**	H_2 system initiating event	Unignited H_2 Release	Leak no ignition	SPAIN	2021-11-10

10 APPENDIX B – CSB CASE DESCRIPTION INVOLVING H_2, BUT NOT APPLICABLE TO BLENDED H_2 PIPELINES

10.1 Silver Eagle Refinery Catastrophic Pipe Explosion

- On November 4, 2009, a powerful blast wave occurred when a 10-inch diameter pipe catastrophically failed at the bottom of a reactor in a distillate dewaxing unit. The pipe released H_2, which caught fire immediately and exploded. The investigation found that the failed pipe had no record of ever being inspected for corrosion as it thinned over the years. Sulfur compounds in the process stream corroded a steel piping segment, causing the pipe walls to become severely thin.
- *Does not apply to transmission pipelines: This incident occurred in a chemical plant.*

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11 APPENDIX C – IEA PROJECT DESCRIPTIONS INVOLVING H_2, BUT NOT APPLICABLE TO BLENDED H_2 PIPELINES

11.1 IEA Ref. PiP-3 – H_2 pipeline Dow-Yara

- In 2018, this 7.5 miles (12 km) long onshore pipeline in the Netherlands became operational[110].
- This pipeline was the first Gasunie natural gas transmission pipeline repurposed for H_2 transport.
- The pipeline transports 4 kt/yr of H_2 from the crackers of Dow Benelux to the user Yara (see Figure 53). Connections were made at Dow, Yara, and ICL-IP, and the gas transport pipeline was modified at a few points to make it suitable for transporting H_2.
- *This project involves a 100% H_2 transmission pipeline without H_2 blending.*

Figure 53. Screen Capture of Video Showing H_2 Pipeline Route from Dow to Yara, Near Terneuzen, The Netherlands[110]

11.2 IEA Infra. Data Ref. BLE-1 (IEA Prod. Data Ref. 734) – HyP SA-Hydrogen Park South Australia (up to 5 to 10% H_2/NG)

- Hydrogen Park South Australia (HyP SA) is the first renewable gas project owned and operated by Australian Gas Networks (AGN). The project uses the existing NG distribution piping network[111,112,113] (see Figure 54). A map showing the location of this and other Australian H_2 projects is given in Figure 55. The logos of AGN and HyP SA are shown in Figure 56.

- Since May 2021, AGN has produced renewable H_2 using renewable electricity and water, supplying more than 700 homes near HyP SA with a blend of up to 5% (by volume) H_2 in NG.

- In March 2023, 3,000 additional customers were added, including households, businesses, and schools.

- In March 2024, blending increased from up to 5% to up to 10% (by volume) H_2/NG blend.

- (Distribution) pipelines deliver the up to 10% H_2/NG blend, and 100% H_2 is delivered by compressed gas by tube trailers to industrial users.

- *This project involves a 10% H_2/NG blend in distribution piping but does not involve transmission pipelines.*

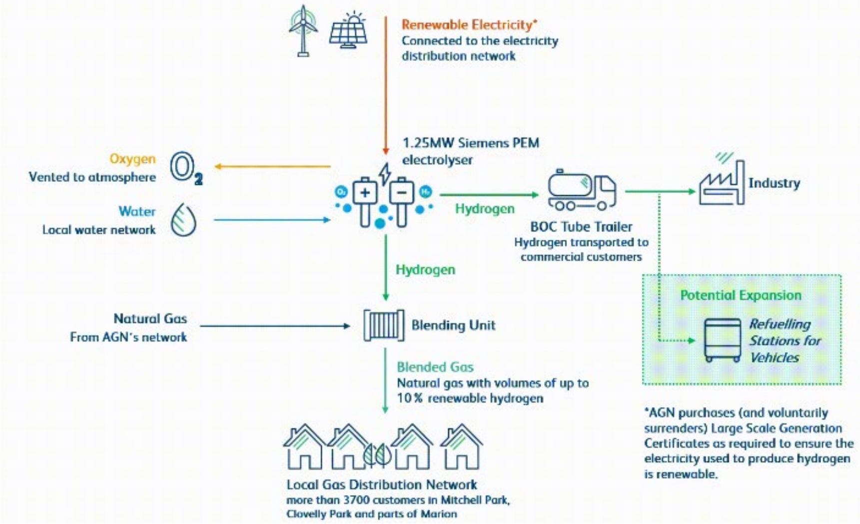


Figure 54. Project Overview of HyP SA[111]

Figure 55. Location of Hydrogen Projects in Australia[112]

Figure 56. AGN and HyP SA Logos[111]

11.3 IEA Infra. Data Ref. BLE-4 – Community Blending Project – Western Australia (2 to 5% H_2/NG)

- At the end of 2022, ATCO started injecting 2 to 5% H_2 into a portion of the NG distribution network around Calleya Estate, Treeby Estate, and Glen Iris in Cockburn, serving approximately 2,700 customers[114] (see Figure 57).

- The long-term goal of blending is up to 10% H_2 network-wide by 2030.

- H_2 is produced renewably via electrolysis, blended with NG, and delivered through ATCO's existing distribution pipelines network.

- *This project is operational, involves a 2 to 5% H_2/NG blend, and has distribution pipelines.*

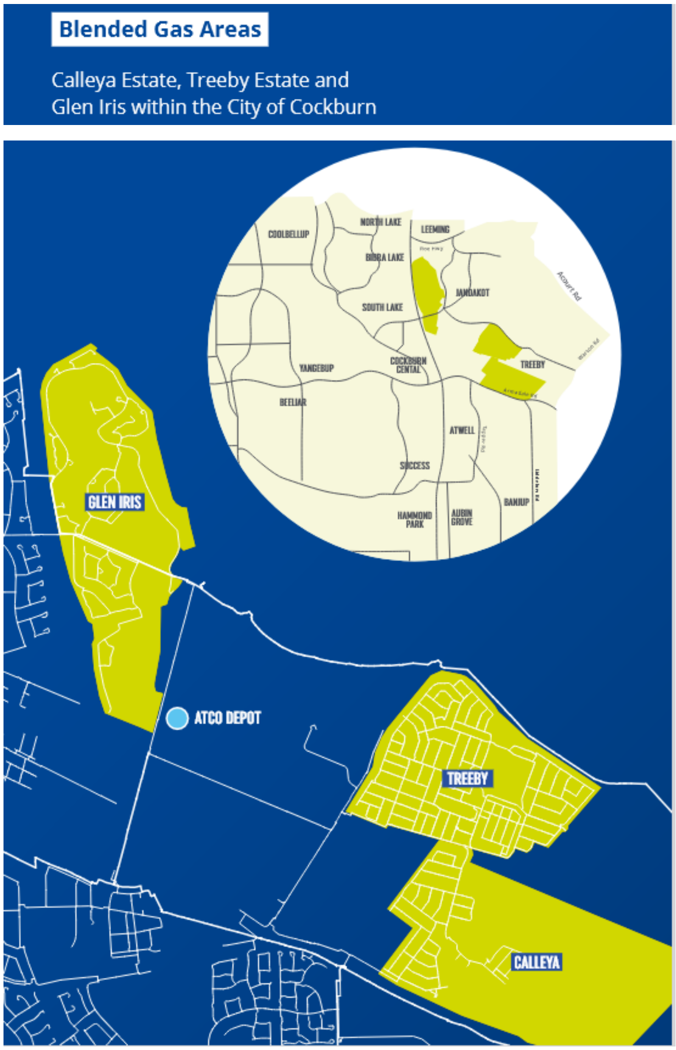


Figure 57. Area of ATCO's Blended Gas Project in Western Australia[114]

11.4 IEA Infra. Data Ref. BLE-7 – Hydrogen Blending Project – Fort Saskatchewan, Alberta, Canada (0 to 20% H_2/NG)

- In 2022, ATCO began delivering a blend of 0 to 5% H_2/NG by volume into a subsection of the Fort Saskatchewan NG distribution system[115], serving approximately 2,100 customers (see Figure 58).

- H_2 was temporarily sourced from local providers. Since late 2024, it has been provided by an on-site electrolyzer. The blend now contains up to 20% H_2 in NG.

- Due to supply chain and other issues, a consistent supply of H_2 cannot be guaranteed. Customers may, therefore, receive anywhere from 0 to 20% blended gas during lower supply times.

- During the planning phase, a pilot project included detailed assessments and rigorous testing on the impacts of 5% and 20% H_2 use on common NG appliances such as stoves, furnaces, hot water heaters, and more.

- *This project is operational, involves 0 to 20% H_2/NG blend, and has distribution pipelines.*

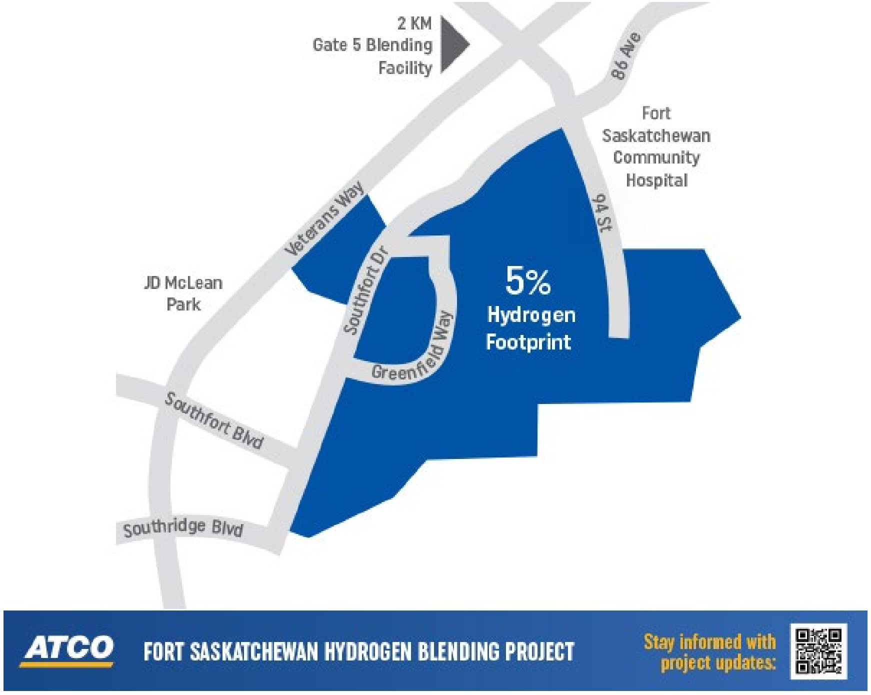


Figure 58. Area of ATCO's Blended Gas Project in Fort Saskatchewan, Alberta, Canada[115]

11.5 IEA Infra. Data Ref. BLE-8 / IEA Prod. Data Ref. 33 – Hydrogen-Blending Pilot in Markham, Ontario, Canada (unspecified % H_2/NG)

- In 2022, Enbridge Gas, Inc., and project partner Cummins, Inc., announced the H_2/NG blending initiative in Markham was fully operational[116] serving approximately 3,600 customers.

- The Markham Power-to-Gas facility stores surplus electricity as pure H_2, which is blended into Enbridge's existing NG framework. The percentage of H_2 blending into NG is not specified on the website. A photograph of the blending facility is shown in Figure 59.

- *This project is operational, involves an unspecified % H_2/NG blend, and has distribution pipelines.*

Figure 59. Hydrogen Blending Facility in Markham, Ontario, Canada[116]

11.6 IEA Infra. Data Ref. BLE-9 / IEA Prod. Data Ref. 1321 – H2GN Project, Gasvalpo Energas Coquimbo – Chile (20% H_2/NG)

- In December 2022, Gasvalpo, through its brand Energas, started producing and injecting up to 20% green H_2 into its NG distribution networks in Coquimbo and La Serena[117], serving more than 2,000 households and shops. The project "H_2GN 2021" is monitored by the University of La Serena.

- H_2 is produced using renewable energy, such as wind and solar. A photograph of the blending facility is shown in Figure 60.

- *This project is operational, involves a 20% H_2/NG blend, and has distribution pipelines.*

Figure 60. Hydrogen Blending Facility in La Coquimbo, Chile[117]

11.7 IEA Infra. Data Ref. BLE-10 / IEA Prod. Data Ref. 1609 – Promigas, Surtigas-Heroica – Cartagena, Colombia (unspecified % H_2/NG)

- In March 2022, Promigas and Surtigas launched a pilot of green H_2 production and injection into NG networks in the Mamonal area in Cartagena, Colombia[118,119,120] (see Figure 61). The project is located at the "Heroica" station in Cartagena.

- In its first phase, 1,574 kg/yr of H_2 was produced and blended with NG. At the end of the fifth phase, up to 15 tons/yr of H_2 can be produced.

- *This project is operational, involves an unspecified % H_2/NG blend, and has distribution pipelines.*

Figure 61. Festive Opening of Green Hydrogen Project in Cartagena, Colombia[119]

11.8 IEA Infra. Data Ref. BLE-12 / IEA Prod. Data Ref. 127 / Ref. CPUC-12 / Ref. PM-12 – WindGas Haßfurt - Germany (4 to 5% H_2/NG)

- In October 2016, Windgas Haßfurt GmbH started producing green H_2 from excess wind and solar energy[121,122].

- Haßfurt's energy landscape is characterized by diverse renewable sources, including solar, wind, and locally produced biogas.

- The water used in the 1.25 MW PEM electrolyzer (see Figure 62) is demineralized before use, and H_2 is dried before inserting into the gas network.

- The production of H_2 will be variable based on the demand for electricity in the electric network and the availability of excess electricity. The IEA database indicates that a blend of 4 to 5% H_2/NG is made in this project. The gas is intended only for local distribution in Haßfurt.

- *This project is operational, involves an unspecified % H_2/NG blend, and has distribution pipelines.*

Figure 62. Electrolyzer in Haßfurt, Germany[121]

11.9 IEA Infra. Data Ref. BLE-13 – Freiburg Municipal Energy Network – Gundelfingen, Germany (up to 1% H_2/NG)

- In 2017, a power-to-gas plant was started in Freiburg Nord, Germany[123] to supply H_2 to Gundelfingen, which has approximately 12,000 people.

- The Fraunhofer Institute provided various analyses and an operation algorithm supporting the project. The concept is shown in Figure 63, and lessons learned are summarized in Figure 64.

- A major finding was that the % of H_2 blending will be highly variable and depends on the electricity supply price, cost incentives, and network energy demand.

- *This project is operational, involves a 0 to 1% H_2/NG blend, and has distribution pipelines.*

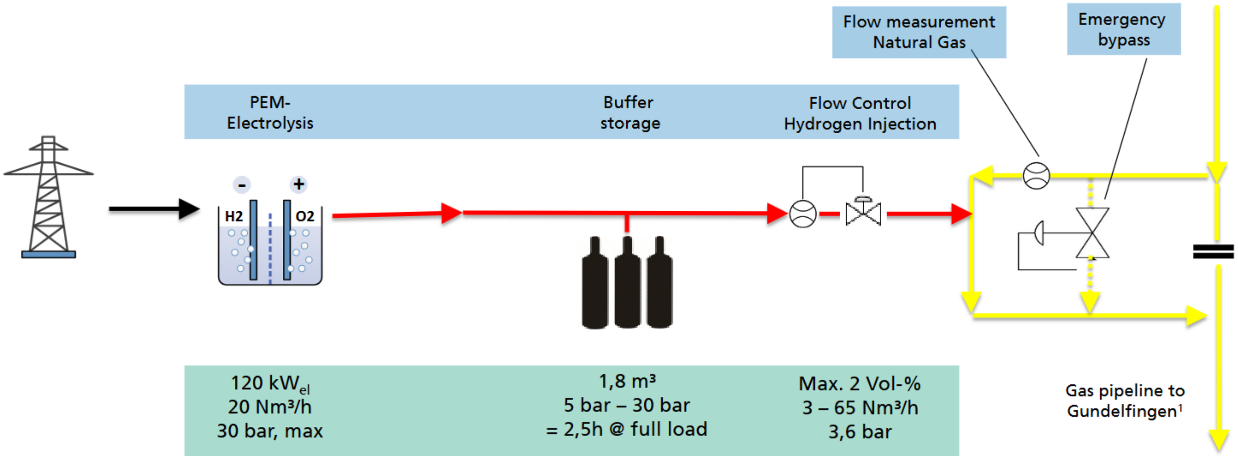
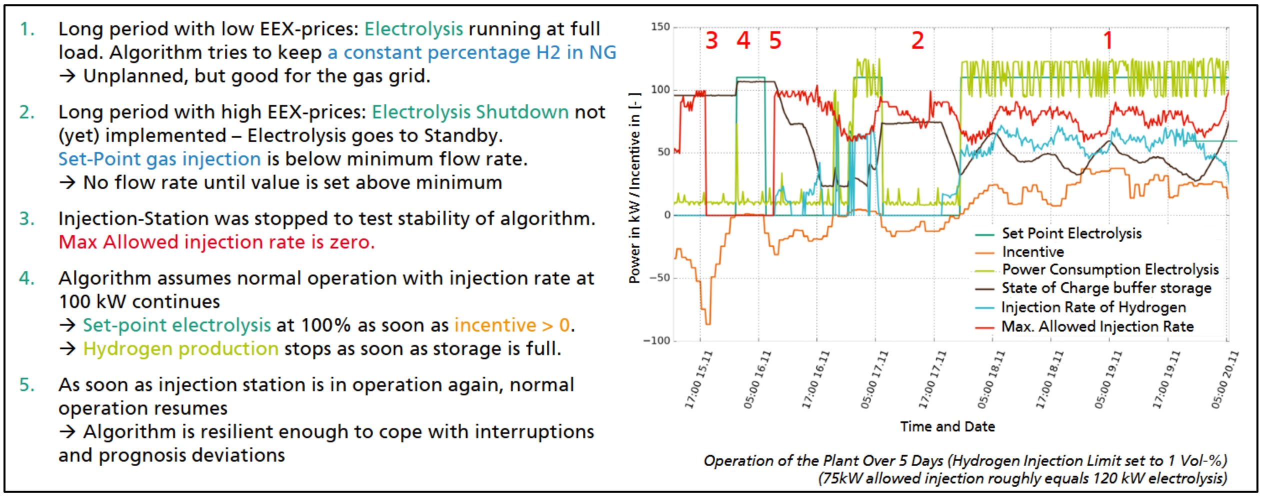


Figure 63. Power-to-Gas Concept in Freiburg Nord, Germany[123]



1. Long period with low EEX-prices: Electrolysis running at full load. Algorithm tries to keep a constant percentage H2 in NG
→ Unplanned, but good for the gas grid.
2. Long period with high EEX-prices: Electrolysis Shutdown not (yet) implemented – Electrolysis goes to Standby.
Set-Point gas injection is below minimum flow rate.
→ No flow rate until value is set above minimum
3. Injection-Station was stopped to test stability of algorithm.
Max Allowed injection rate is zero.
4. Algorithm assumes normal operation with injection rate at 100 kW continues
→ Set-point electrolysis at 100% as soon as incentive > 0.
→ Hydrogen production stops as soon as storage is full.
5. As soon as injection station is in operation again, normal operation resumes
→ Algorithm is resilient enough to cope with interruptions and prognosis deviations

Operation of the Plant Over 5 Days (Hydrogen Injection Limit set to 1 Vol-%)
(75kW allowed injection roughly equals 120 kW electrolysis)

Figure 64. Lessons Learned from Power-to-Gas Concept in Freiburg Nord, Germany[123]

11.10 IEA Infra. Data Ref. BLE-21 – Hydrogen Blending - Indore, Madhya Pradesh, India (up to 2% H_2/NG)

- In November 2023, state-owned GAIL (India) Ltd[124] started a project designed to produce approximately 4.3 metric tons of H_2/day (approximately 10 MW capacity) using a PEM electrolyzer at GAIL's Vijaipur Complex in Guna District of Madhya Pradesh.
- Initially, the produced H_2 was used as fuel along with NG for various processes and equipment within the Vijaipur complex, for example, as a supply to industries such as fertilizer manufacturers. In the future, GAIL plans to distribute H_2 to retail customers in nearby areas.

- In July 2023, GAIL increased the blending from 2 to 5% H_2 for 3,000 households and 70 industrial and commercial units. At that time, approximately 200 kg/day (13,000 standard m^3/day) of H_2 was being injected into the Avantika Gas Limited's (AGL's) NG network.

- In January 2022, GAIL commenced India's first-of-its-kind project of mixing H_2 into the NG system. Two percent (2%) H_2 blended NG was being supplied to one of GAIL's joint venture companies with Hidustan Petroleum Corporation Ltd. (HPCL) -- AGL, which is a city gas distribution (CGD) company operating in Indore, Madhya Pradesh.

- *This project is operational, involves a 2% H_2/NG blend, and does not mention a transmission pipeline.*

11.11 IEA Infra. Data Ref. BLE-22 / IEA Prod. Data Ref. 1970 – NTPC-GGL in Surat - Kawas Township at Adityanagar, Surat, India (5 to 20% H_2/NG)

- In January 2023, NTPC Ltd. and Gujarat Gas Limited (GGL) started blending H_2 into the piped natural gas (PNG) network of NTPC Kawas Township, Surat[125]. The green H_2 is generated in a 6.5 kW PEM electrolyzer using power from a 1 MW floating solar project. A photograph of the equipment is shown in Figure 65.

- The Petroleum and Natural Gas Regulatory Board (PNGRB), the regulatory body, has approved starting 5% by volume H_2/NG blending and scaling it phase-wise to 20%.

- *This project is operational, involves a 5 to 20% H_2/NG blend, and does not mention a transmission pipeline.*

Figure 65. Electrolyzer, H_2 Storage, and Blending Skid in Kawas Township at Adityanagar, Surat, India[125]

11.12 IEA Infra. Data Ref. BLE-23 – Floene “Natural Energy of Hydrogen” project – Seixal, Portugal (up to 20% H_2/NG)

- In March 2023, Floene, a gas distribution company, (previously named Galp Gás Natural Distribuição) started blending green H_2 into Seixal’s NG distribution network[126, 127].

- Floene Energias, S.A. (a joint venture between Toho Gas and Marubeni Corporation) transports the H_2 through its newly constructed 100% H_2 pipeline, injects it into its existing NG network, and distributes the H_2/NG blend to 82 residential, tertiary, and industrial customers. After a test phase with 10 to 15% H_2, these customers are supplied with a mixture of green H_2 and NG, increasing to a maximum of 20% H_2.

- H_2 is produced locally using 100% renewable energy in the Seixal Industrial Park by the Portuguese company, Gestene. After being produced and stored (see Figure 66), the H_2 travels 0.87 miles (1.4 km) in a PE pipeline to a station where it is mixed with NG and then distributed to customers. PE is used in approximately 95% of the gas network used in Portugal.

- "The Natural Energy of Hydrogen" project has institutional partners with the Seixal City Council and the Environmental Fund, and as technical partners with Bosch, Catim, Gestene, ISQ, PRF, the Higher Technical Institute and Portuguese Association for the Promotion of Hydrogen – HP2H.

- *This project is operational, involves up to 20% H_2/NG blend, and has a 100% H_2 pipeline.*

Figure 66. Introduction of “The Natural Energy of Hydrogen” Project in Seixal, Portugal[125]

11.13 IEA Prod. Data Ref. 1301 – H2Évora GreenGas II – Portugal (up to 15% H_2/NG)

- In January 2023, Fusion Fuel, an electrolyzer technology company, announced a green H_2 offtake agreement with Portuguese NG distribution utility Dourogás[128, 129]. The project uses solar power to generate H_2 gas. Dourogás will be able to use the H_2 in its domestic, industrial, and natural gas for vehicles (NGV) mobility segments.

- The first H_2 to be blended will be produced at Fusion Fuel's GreenGas project in Évora. It is planned to produce 40 tons/yr of H_2.
- Floene (previously named Galp Gás Natural Distribuição) is expected to build the infrastructure to enable blending in the grid. Floene's grid connects around 1.13 million households across Portugal, with approximately 8,387 miles (13,498 km) of pipelines, distributing approximately 1.7 billion m^3/yr of gas.
- Portugal's national H_2 strategy, "National Plan Energy and Climate 2021-2030", adopted in 2020, laid out high-impact targets, including a 15% blend of H_2 in its natural gas distribution network and 2 GW of electrolyzer capacity by 2030.
- The "H2Évora GreenGas II" P2G Phase 2 project follows a prior demonstration power-to-gas-to-power (P2G2P) Phase 1 project "H2Évora," which is a solar plant that produces 15 tons/yr of H_2 and uses a 200 KW fuel cell supplied by Ballard Power Systems to later convert green H_2 back into electricity (see Figure 67).
- *This project is operational, involves 15% H_2/NG blending, and has a large gas pipeline network.*

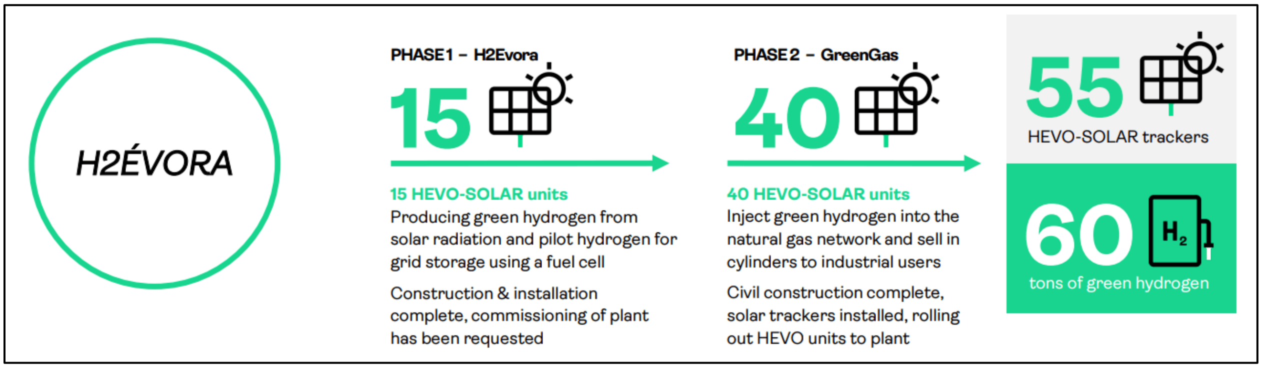


Figure 67. H2Évora (Phase 1) and GreenGas (Phase 2) Projects by Fusion Fuel in Portugal[129]

11.14 IEA Infra. Data Ref. BLE-24 – "20HyGrid" project – Dârlos, Sibiu County, Romania (up to 20% H_2/NG)

- In 2023, Delgaz Grid, a company from the E.ON Romania group, started tests on the operation of networks and devices for the use with a 20% H_2/NG blend[130, 131] for 75 households in Dârlos, Sibiu County, Romania.
- All households were located along the same street, and H_2 was supplied from compressed gas cylinders (see Figure 68). The NG distribution system was a polyethylene piping grid.

- In May 2023, for the same project, Delgaz started tests at the Mediaş training ground, aiming to validate the use of the technological solution based on the mixture of 23% H_2 with NG. In a mini-distribution network, the company tested existing thermal plants, older models (without condensation) installed before 2015, and condensing plants produced after 2015 (new generation devices), which are ready for 23% H_2.
- The Green Forum[132] states:

> "For scientific and technical reasons, it is possible to introduce quantities of up to 20-30% hydrogen, without relevant changes to end users and infrastructure or pipelines."

- *This project is operational, involves up to 20% H_2/NG blend, and has no (steel) transmission pipeline.*

Figure 68. H_2 was Supplied from Gas Cylinders in Dârlos, Romania

11.15 IEA Infra. Data Ref. BLE-25 – CenterPoint Energy – Minneapolis, MN, United States (up to 5% H_2/NG)

- In June 2022, CenterPoint Energy announced that its green H_2 project in Minneapolis is operational[133,134]. This pilot project is located on existing company property near downtown Minneapolis. It uses a 1 MW electrolyzer that can produce 432 kg of H_2/day and is powered by renewable energy (see Figure 69).
- H_2 is blended at low concentrations, up to 5%, with NG in the utility's local distribution system.

- *This project is operational, involves up to 5% H_2/NG blend, and has no transmission pipeline.*

Figure 69. Electrolyzer Delivery at CenterPoint Gas Facility in Minneapolis, USA[134]

11.16 IEA Infra. Data Ref. BLE-26 – "Therm H2" Pilot Project – Delta, UT, United States (up to 5% H_2/NG)

- In 2021, Dominion Energy Utah (DEU) started the first phase of the Therm H2 project[135], focusing on blending H_2 at the utilities' training academy, to confirm the feasibility of currently available H_2 research.

- In the first phase, a 5% H_2 blend was evaluated for almost a year, and it was found that H_2 was safely compatible with current residential appliances.

- The next phase involves blending H_2 into the distribution system of Delta, UT, and the surrounding towns of Oasis, Hinkley, and Deseret, which serves approximately 1,800 customers. The project started with gray H_2 but will be upgraded to green H_2.

- Coincidentally, Delta, UT, is home to the Therm H2 project for local blended H_2/NG distribution and the conversion of coal plant to blended H_2/NG (refer to Section 7.10.4 above.)

- *This project is operational, involves up to 5% H_2/NG blend, and has no transmission pipeline.*

11.17 IEA Infra. Data Ref. BLE-28 – "HyGrid" Project - Town of Hempstead, Long Island, NY, United States (5 to 20% H_2/NG)

- In December 2021, National Grid and the Town of Hempstead announced a joint project to build a clean H_2 project[136,137] blending 5 to 20% H_2. The H_2/NG blend is used for heating approximately 800 homes and for transport 10 municipal vehicles simultaneously (see Figure 70).

- Previously, in 2009, Hempstead developed an H_2 facility to provide locally produced green H_2 for vehicles. Thus, much of the equipment was already in place at the site, including existing wind and solar equipment for generating H_2 fuel for vehicles and an adjacent facility (owned by gas distribution company National Grid) that provides energy for the local neighborhood.

- *This project is operational, involves 5 to 20% H_2/NG blend, and has no transmission pipeline.*

Figure 70. Event to Announce Expansion of H_2 Facility in Town of Hempstead, Long Island, NY, United States[136]

11.18 IEA Prod. Data Ref. 258 – Hybrid Power Plant Enertrag – Town of Prenzlau, Germany (unspecified % H_2/NG)

- In 2011, wind energy supplier ENERTRAG AG started operating a power plant[138, 139, 140], which, in times of oversupply, can convert surplus electricity into H_2 (see Figure 71 and Figure 72).

- This power-to-gas project combines a wind energy plant, an H_2 generation facility, and a heat and power plant. The capability to store unused electricity as H_2 gas helps stabilize the power grid and provides a model for the future use of renewable energies.

- On days of high energy demand, H_2 is converted back into electricity in a combined heat and power plant. Before use, the H_2 is mixed with biogas to achieve ideal output levels.

- The waste heat from this process is used as district heating for the nearby town of Prenzlau, through the existing gas grid ONTRAS Gastransport GmbH. Any superfluous H_2 is turned into fuel for H_2 cars and brought to petrol stations in Berlin.

- *This project is operational, involves an unspecified H_2/NG blend, and has no pipeline.*

Figure 71. H_2 Storage Tank at Hybrid Power Plant in Prenzlau, Germany[139]

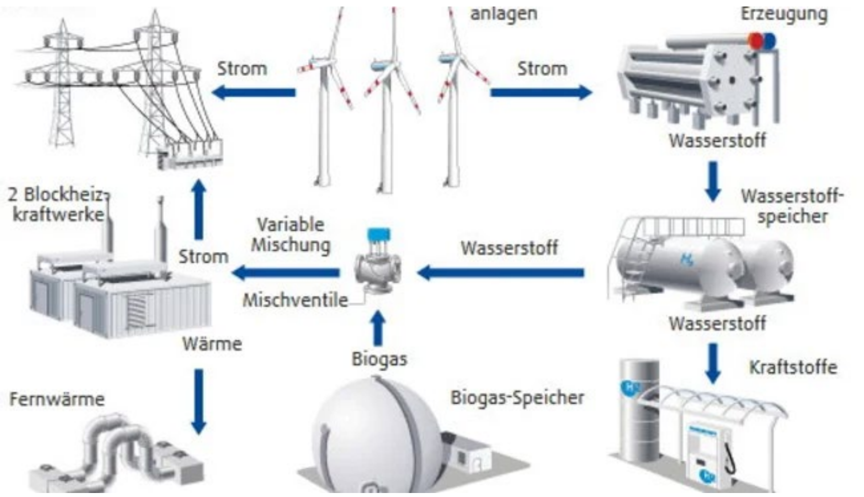


Figure 72. Schematic of H_2 Generation, Storage, and Blending at Hybrid Power Plant in Prenzlau, Germany[140]

11.19 IEA Prod. Data Ref. 240 – EUCOlino Biogas Project – Schwandorf, Germany (unspecified 1% H_2/CH_4 biogas blend)

- Since November 2012, MicrobEnergy has operated an EUCOlino plant to produce 21 normal m^3/hr of H_2 or 5 normal m^3/hr of synthetic CH_4[141], using biogas as a CO_2 source (see Figure 73).

- In contrast to catalytic methanation, here methanation is achieved biologically (anaerobic digestion) with microorganisms in-situ in the fermenter of the biogas plant.

- Synthetic methane and biogas are used locally for electricity production.

- *This project is operational, involves an unspecified % of H_2/CH_4 biogas blend, and has no transmission pipeline.*

Figure 73. Compact Biogas Plant "EUCOlino" in Schwandorf, Germany[141]

11.20 Second WindGas Project – Falkenhagen, Prignitz, Brandenburg, Germany (up to 2% H_2/NG)

- In March 2016, a second "WindGas Falkenhagen" demonstration project was initiated in the international STORE&GO initiative as part of Horizon 2020, the European Union's research and innovation program[62, 63, 64] to create CH_4 from green sources.
    - In July 2017, construction started on a methanation plant next to the existing pure H_2 PtG plant (see Figure 74).
    - By May 2018, production started at 57 m^3/hr of SNG and process heat for a nearby veneer plant.
    - The project combines 210 m^3/hr of H_2 from the PtG facility with 52.5 m^3/hr of CO_2 sourced from a bio-ethanol plant located in Zeitz.
    - In January 2019, the project was completed with the first gas injection into the ONTRAS grid, producing up to 1,400 m^3/day of SNG.

- *This project is operational, but does not involve H_2 blending, and has no transmission pipeline.*

Figure 74. PtG Plant - Falkenhagen, Germany [63]

- Two other STORE&GO demonstration projects that do not involve H_2 blending are:
    - A plant that collects CO_2 from the air and matches it to H_2 from electrolyzers to produce CH_4 fuel in Apulia, Troia, Italy[142].
    - A plant that receives CO_2 from a wastewater treatment plant and reacts it with H_2 in a biological methanation process to produce SNG in Solothurn, Switzerland[143].
    - *These projects are operational, but do not involve H_2 blending, and have no transmission pipeline.*

11.21 IEA Prod. Data Ref. 907 – Green Hydrogen Esslingen (P2G2P) – Neue Weststadt, Esslingen, Germany (unspecified % H_2/NG)

- In March 2019, "Green Hydrogen Esslingen" was founded by Polarstern Erzeugungs GmbH, Prof. Dr. Norbert Fisch of Technische Universität Braunschweig, and the municipal utilities of Esslingen, in Germany[144,145,146]. Together, they created an urban district, the "Neue Weststadt (New West City)," for local energy use and research, including H_2 (see Figure 75).
- In June 2021, an energy center was inaugurated.
- In 2022, an electrolyzer was installed. A wind turbine whose funding expired at the end of 2021 but had a projected 10+ years of remaining life was dedicated to power the electrolyzer. In addition, the electrolyzer receives its power from solar surplus electricity.

- The green H_2 is used to power the urban residential development "Klimaquartier" in Esslingen, which includes 500 apartments, office and commercial space, and a university campus.

- At Klimaquartier, solar power is harvested locally from room panels. Biomethane is used for heating and cooking. Surplus electricity from the roof and wind energy is converted to H_2 using a local electrolyzer. H_2 is blended to create an H_2/NG blend and fed locally into the NG grid via pipes. Waste heat from the electrolyzer is used to heat apartments.

- Another plan involves a pipeline between Stuttgart's port and Esslingen, which would get the green H_2 from Neue Weststadt directly to factories and truck tanks.

- *This project is operational, involves an unspecified % of H_2/NG blend, and has no transmission pipeline.*

Figure 75. Neue Weststadt in Esslingen, Germany[144]

11.22 IEA Prod. Data Ref. 286 - H2KT Hydrogen Energy Storage – Nuuk, Greenland, Denmark (No % H_2/NG blending)

- In February 2010, the H2KT project was started by Greenland's national energy company Nukissiorfiit, with the successful opening of the first test/demonstration plant to store surplus hydro-power energy in the form of H_2 in Nuuk, Greenland[147,148] (see Figure 76 and Figure 77).

- The plant was located at the company's headquarters. H_2 and fuel cell plants provided electric energy to the headquarters building.

- Phase 1 of the project was a short-duration (one-month) effort. Phases 2 and 3 were considered, with possible uses of stored H_2 as follows:
  - Conversion to electricity and heat in a fuel cell;

  - Distribution to cities/settlements by tanker truck;
  - As fuel for transportation;
- The use of O_2 from the electrolysis at a local hospital was considered; and
- This project did not involve a pipeline and did not involve blending.
- No information about Phase 2 and/or Phase 3 was found online.
- *This project is no longer operational, involved no H_2/NG blending, and had no transmission pipeline.*

Figure 76. Test Plant in Nuuk, Greenland, Denmark[147]

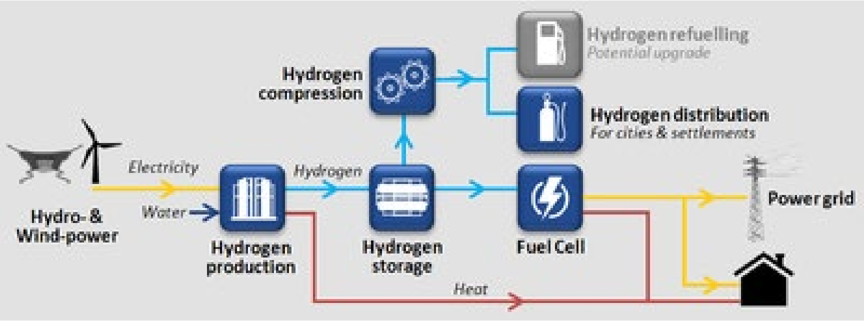


Figure 77. Concept of H2KT Project in Nuuk, Greenland, Denmark[148]

11.23 IEA Prod. Data Ref. 71 - HyBALANCE – Hobro, Denmark (unspecified 2% H_2/NG)

- In 2018, one of Europe's first, biggest, and most advanced facilities was inaugurated in Hobro, Denmark[149,150] (see Figure 78).

- The HyBALANCE plants led power from the electricity grid into a 1.2 MW PEM electrolyzer. By September 2020, the facility had delivered 120 tons of H_2. The facility ran 24/7 and demonstrated that large-scale H_2 storage is possible.

- Fifty percent (50%) of the H_2 was used to supply a neighboring industrial complex through a pipeline. The other 50% was delivered by tube trailers to other industries and for transportation, including a fleet of H_2 taxis in Copenhagen.

- In 2020, the project was concluded as planned. AirLiquide continues to operate the plant for its customers.

- *This project is operational, does not involve H_2/NG blending, and does involve a transmission pipeline.*

Figure 78. HyBALANCE Plant in Hobro, Denmark[150]

11.24 IEA Prod. Data Ref. 2467 – Jorhat H2 – Assam, India (unspecified % H_2/NG)

- In April 2022, India's first pure green H_2 pilot plant anion exchange membrane (AEM) electrolyzer technology was commissioned at the Jorhat Pump Station in Assam by Oil India Limited (OIL), a government of India enterprise[151,152] (see Figure 79).

- H_2 is produced from solar power in a 100 kW AEM electrolyzer. Production is expected to increase from 10 kg/day H_2 to 30 kg/day H_2.

- OIL plans to study cases for commercial applications of blended H_2/NG fuel and its effect on the existing infrastructure of OIL.

- The project description does not mention H_2 blending or a pipeline.

- *This is one of the few projects that aims to address the effects of integrity on infrastructure.*

- *This project is operational, does not involve H_2/NG blending, and no transmission pipeline.*

Figure 79. H_2 Facility at Jorhat Pump Station, Assam, India[152]

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Table 10. U.S. Operational Production Projects for Hydrogen Gas for Any Purpose, from IEA Hydrogen Production and Infrastructure Projects Database, as of November 2024[54]

#	IEA Infra. Ref.	Project Name	Date Online	Technology	Electric	H_2 Gas	Transport	Ref.
1	1240	3 x 1250 kW projects in USA	2000	PEM	3 x 1250 kW			
2	1241	1 x 500 kW projects in USA	2000	PEM	500 kW			
3	1243	18 x 180 kW projects in USA	2000	PEM	18x180 kW			
4	1245	12 x 120 kW projects in USA	2000	PEM	12x120 kW			
5	1956	Plug Power Charleston, Tennessee (former United Hydrogen) (TN)	2008	PEM		6.5 t H_2/d	Liquid H_2 transport by truck	153
6	708	Port Arthur (TX)	2013	NG (SMR) with CCUS		900,000 t CO_2/y, 151,000 m^3 H_2/h	H_2 used in refinery CO_2 transmission by pipeline	154
7	70	SunLine Transit Agency (CA)	2018	PEM	1.5 MW		H_2 used in fuel cell buses	155
8	934	SunLine Palms Springs (CA)	2018	PEM	2 MW		H_2 used in fuel cell buses	156
9	735	NEL-Champaign-Urbana Mass Transit District (IL)	2021	PEM	1 MW		H_2 used in fuel cell buses	157
10	781	Olive Creek 1 (NE)	2021	Methane pyrolysis with CCS		15 kt CO_2/y 5 kt H_2/y	H_2 used in process plant	158
11	953	New Jersey Resources Howell (NJ)	2021	Other Electrolysis: Unknown PtX	175 kW	60 kg H_2/d	8-inch, 60 psig distribution pipeline for H_2/NG blending	61
12	1957	Plug Power Charleston, Tennessee (former United Hydrogen), expansion 1 (TN)	2021	PEM		10 t H_2/d	Liquid H_2 transport by truck	153
13	769	Air Liquide liquid hydrogen production plant (North Las Vegas, NV)	2022	Only part from biogas, but at least 1/3		30 t H_2/d	Liquid H_2 for fuel cell vehicles	159, 160

#	IEA Infra. Ref.	Project Name	Date Online	Technology	Electric	H_2 Gas	Transport	Ref.
14	836	Long Beach Fuel Cell plant (CA)	2023	Biomass - Biogas reforming		1.2 kg H_2/d	Liquid H_2 for fuel cell vehicles at a port	161
15	941	Cavendish NextGen Hydrogen Hub (FL)	2023	PEM	25 MW		5% blend H_2 in NG used in onsite gas turbine	162
16	1100	BayoTech - St Louis Hub (MO)	2023	NG w CCUS - Unknown technology		350 t H_2/y	High-pressure H_2 gas transport by trailers	163
17	1141	SoHyCal (CA)	2023	PEM	7.5 MW	1.2 t H_2/d	High-pressure H_2 gas transport by trailers	164
18	1521	Montana Renewables (MT)	2023	Other Electrolysis: Unknown PtX			H_2 to make sustainable aviation fuel	165
19	1986	Constellation - Nine Mile Point Nuclear Plant (NY)	2023	PEM	1 MW	560 kg H_2/d	H_2 for onsite use at nuclear plant	166
20	1182	Camden County (GA), green power plant	2024	PEM	40 MW	15 t H_2/d	Liquid H_2 transport by truck	167

Table 11. Global Operational Production Projects for Hydrogen Gas for Grid Injection (H_2 Blending), from IEA Hydrogen Production and Infrastructure Projects Database, as of 2024[54]

#	IEA Prod. Ref.	Project Name	Country	Date Online	Technology	Electric	H_2 Gas	Transport	Lit. Refs.
1	734	Hydrogen Park South Australia – HyP SA	Australia	2021	PEM	1.25 MW	20 kg H_2/h	10% H_2/NG Blend for distribution by pipeline (3,700 customers), 100% High-pressure H_2 gas transport by tube trailers	111, 112, 113
2	737	Jemena Western Sydney - H2GO project	Australia	2021	PEM	0.5 MW		(not reported %) H_2/NG Blend for distribution by pipeline; Use by fuel cell onsite; Use to fill H_2 cylinders	55, 56, 57
3	33	Markham Energy Storage, Ontario	Canada	2019	PEM	2.5 MW		(not reported %) H_2/NG Blend for distribution by pipeline (3,600 customers)	116
4	1321	H2GN - Power-to-gas Coquimbo	Chile	2023	Other Electrolysis: Unknown PtX	150 kW		(not reported %) H_2/NG Blend for distribution by pipeline (2,000 customers)	117
5	1609	Promigas	Colombia	2022	PEM	22 kW		(not reported %) H_2/NG Blend for distribution by pipeline	118, 119, 120
6	258	Hybrid Power Plant Enertrag, Prenzlau	Germany	2011	ALK	0.5 MW	120 N m^3 H_2/h	H_2 for onsite use at biogas electric plant (no pipeline)	138, 162
7	240	Eucolino Schwandorf	Germany	2012	Other Electrolysis: Unknown PtX		24 N m^3 H_2/h		141
8	202	WindGas Falkenhagen	Germany	2013	ALK	2 MW		1.2 miles (2 km) 2% H_2/NG pipeline at MOP of 800 psig (55 barg)	62, 63, 64
9	203	P2G plant Erdgas Schwaben	Germany	2013	PEM	1 MW	180 N m^3 H_2/h	No pipeline. H_2 storage for local use.	

#	IEA Prod. Ref.	Project Name	Country	Date Online	Technology	Electric	H_2 Gas	Transport	Lit. Refs.
10	198	Hanau, Wolfgang Industrial Park	Germany	2014	PEM		4 N m^3 H_2/h	No pipeline. H_2 for vehicle transportation	
11	127	Haßfurt	Germany	2016	PEM	1.25 MW			121, 122
12	134	HPEM2GAS (R&D)	Germany	2016	PEM	0.2 MW		No pipeline. Research project	
13	437	Energiepark Mainz	Germany	2017	PEM	6 MW			66, 67, 68, 69
14	80	Windgas Haurup, 1st phase	Germany	2018	PEM	0.225 MW			70, 71, 72
15	52	Stromlückenfüller 2nd phase	Germany	2019	PEM	0.2 MW		No pipeline. H_2 stored for local fuel cells.	
16	68	Wind to Gas Südermarsch	Germany	2019	PEM	2.4 MW	450 m^3 H_2/h		58, 59
17	716	HYPOS (several projects)	Germany	2019	Other Electrolysis: PEM+ALK+SOEC	1.3 MW		Not a specific project. HYPOS is a German industry consortium to develop H_2 technologies.	
18	907	Green Hydrogen Esslingen (P2G2P)	Germany	2021	ALK	0.5 MW			144, 145, 146
19	286	H2KT - Hydrogen Energy Storage in Nuuk	Denmark	2010	ALK		19 N m^3 H_2/h		147, 148
20	71	HyBALANCE	Denmark	2020	PEM	1.5 MW			149, 150
21	246	Hydrogen mini grid system Yorkshire (Rotherham)	Great Brittain	2012	ALK	0.03 MW		No pipeline. H_2 for vehicle transportation	
22	77	Hydrogen plant - Orkney Islands - BIG HIT 1st phase	Great Brittain	2017	PEM	0.7 MW		No pipeline Transport by tanker trucks	
23	22	Hydrogen plant - Orkney Islands - BIG HIT 2nd phase	Great Brittain	2019	PEM	1 MW		No pipeline Transport by tanker trucks	

#	IEA Prod. Ref.	Project Name	Country	Date Online	Technology	Electric	H_2 Gas	Transport	Lit. Refs.
24	42	HyDeploy	Great Brittain	2020	PEM	0.5 MW			77, 78
25	2462	Gwalpahari Solar-Hydrogen demonstration	India	2015	Other Electrolysis: Unknown PtX		19.4 t H_2/y production	No pipeline. H_2 for bus and vehicle transportation	
26	2467	Jorhat H2	India	2022	Other Electrolysis: Unknown PtX		75 t H_2/y production		151, 152
27	1970	NTPC Green Hydrogen Blending Project (Kawas, Surat)	India	2023	PEM	6.5 kW			125
28	279	DNV Kema/DNV GL	Netherlands	2011	PEM	0.01 MW		No pipeline. Research project	
29	1301	H2Évora - GreenGas II	Portugal	2023	PEM		60 t H_2/y		128, 129
30	50	Vårgårda Bostäder housing complex	Sweden	2019	ALK		60 N m^3 H_2/h	No pipeline. No H_2/NG blending	
31	953	New Jersey Resources Howell (NJ)	USA	2021	Other Electrolysis: Unknown PtX	175 kW	60 kg H_2/d	8-inch, 60 psig distribution pipeline for H_2/NG blending	61
32	142	WindGas Hamburg-Reitbrook	DEU	2015	PEM	1.5 MW			62, 63, 64

12 APPENDIX D – PILOT-SCALE AND FULL-SCALE 100% H_2 PIPELINE PROJECTS (NON-BLENDING)

This appendix describes pilot-scale and full-scale pipeline projects for 100% H_2 gas. These projects can involve a new H_2 pipeline or a conversion from another product to an H_2 service pipeline. Although these pipelines are considered non-blended gas, the quality of the "pure" H_2 gas in terms of impurities can be important. Small concentrations of other contaminants in the H_2 environment may inhibit the negative effects of H_2 on the pipeline steels.

12.1 U.K. — Leeds CityGate H21 Project (2016 - Present) — Conversion of Existing NG Network to 100% H_2

The Leeds City Gate H21 Project[5] was a 2016 study to determine the feasibility of converting the existing NG network in Leeds, U.K. to 100% H_2. There is no blending with NG in this case. For appliance design purposes, the specifications for gas contaminants were set as CO < 15 ppm, CH_4 < 100 ppm, and CO_2 < 10 ppm, with H_2 purity > 99.98%. However, the project considered that H_2 was realistically likely to be saturated with water on an occasional basis and may contain significant quantities of dust and other physical impurities. The issue of detecting a leakage by odorization of the H_2 gas was brought up in the 2016 document, but no resolution was provided at that time.

The Leeds study involved conversions of (1) the gas medium pressure (MP) and low pressure (LP) gas distribution networks, (2) appliances, and (3) the H_2 transmission system (HTS). In 2016, the plan was that H_2 would be supplied from a steam methane reformer (SMR), stored in associated storage caverns, and transported to Leeds through a new pipeline. The project team wrote that the technology was well-established and proven. In 2004, based on the operational history of approximately 900 miles (1,448 km) of H_2 pipelines in the U.S. and approximately 930 miles (1,500 km) in Europe.

In 2016, the project anticipated that two new high-pressure pipelines would be required to economically transport H_2 gas from the production facilities (SMRs) and their associated storage caverns to Leeds (see Figure 80). The pipelines would be constructed of L360 steel, have nominal diameters of 16 inches (450 mm) and 24 inches (650 mm), and operate at pressures up to 580 psig (40 barg) (see Table 12). Prior to operation, the pipeline would be subjected to a hydrostatic pressure test and ILI.

The pipeline system would include block valves, inspection facilities, and pressure reduction stations (required to reduce the pressure at the injection points to the medium-pressure system). The report mentioned that currently (2016), no H_2 pipelines in the U.K. run cross-country. However, there are pipelines distributing H_2 to multiple users at chemical complexes.

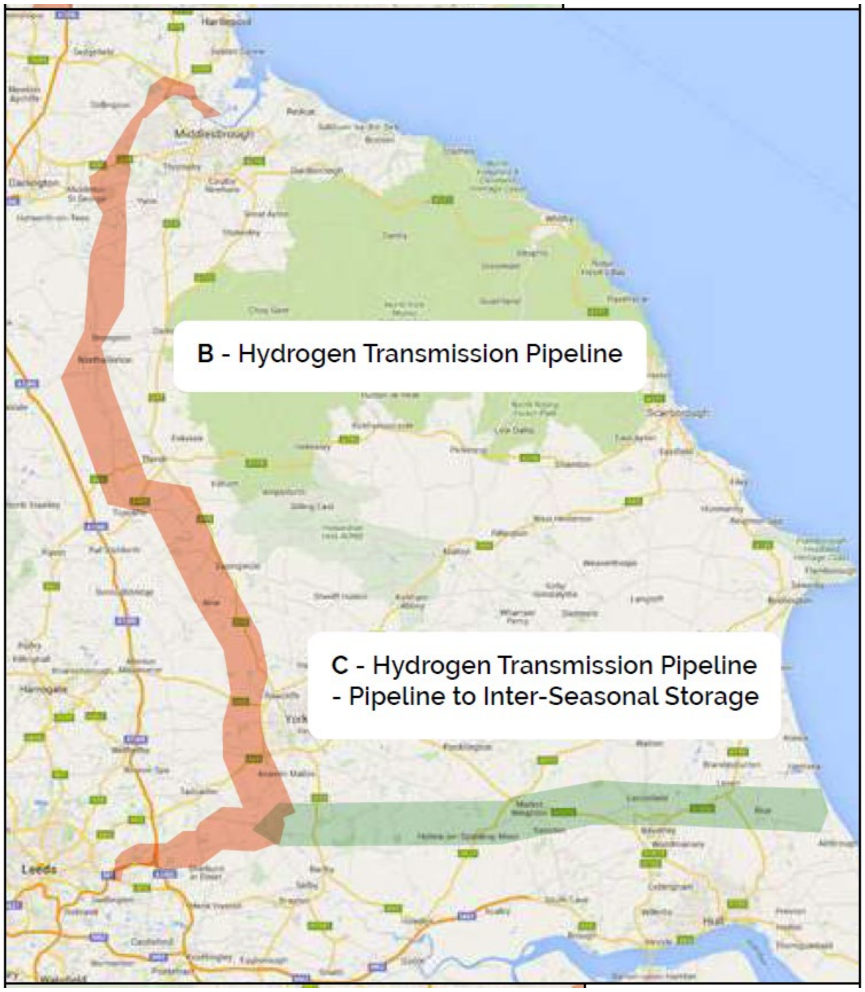
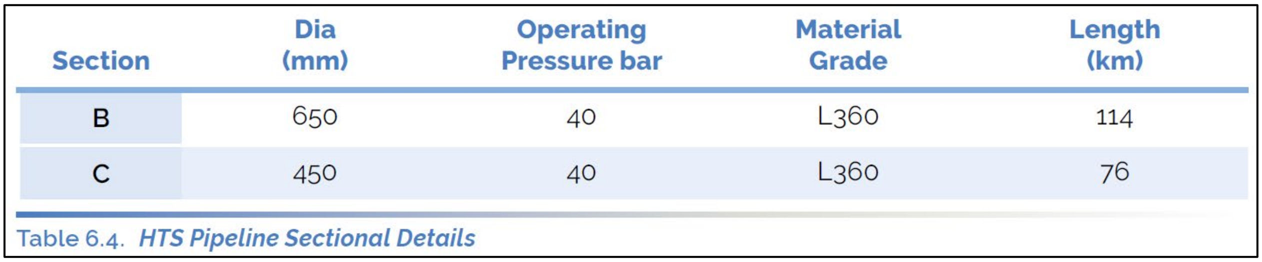


Figure 80. Indicative Route Corridor of Hydrogen Pipelines for Leeds CityGate H21 Project[5]

Table 12. HTS Pipeline Sectional Details[5]

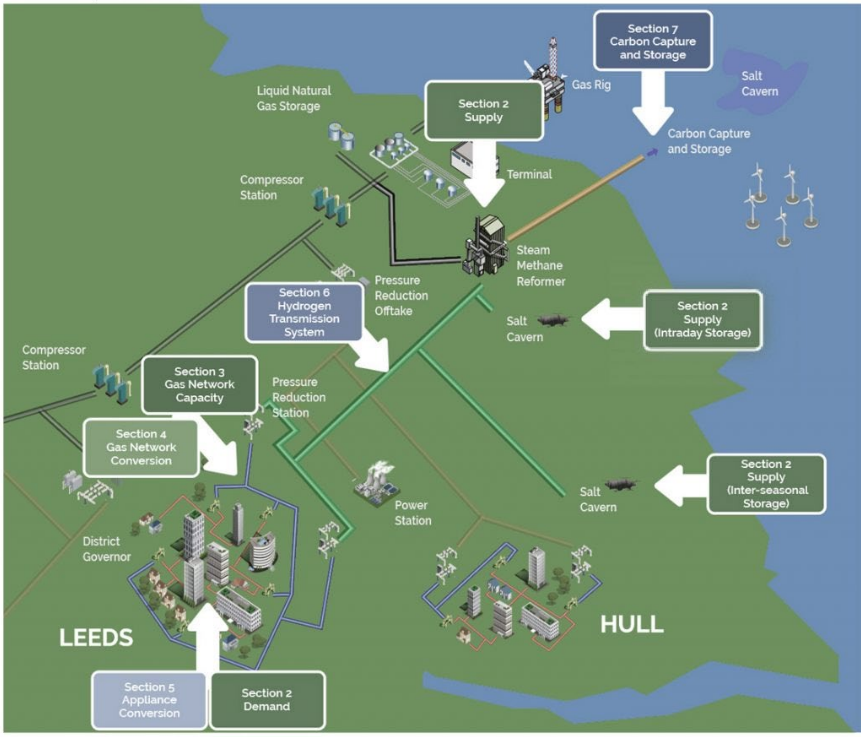


Section	Dia (mm)	Operating Pressure bar	Material Grade	Length (km)
B	650	40	L360	114
C	450	40	L360	76

Table 6.4. *HTS Pipeline Sectional Details*

Watt-Logic[168] reported that Northern Gas Networks (NGN) conducted a first-stage review and is investigating further stages (see Figure 81). The project sought 55 million pounds (approximately $68 million USD) in funding to develop a roadmap to H_2 with further studies. One option is using pure H_2, although various CH_4 blends are also being evaluated. The conversion of Leeds is likely to cost around 2 billion pounds (approximately $2.5 billion USD) and would require the conversion of all domestic appliances for use with H_2.

Leeds city scheme



Source: Northern Gas Networks

Figure 81. Overview of Leeds, U.K. Project (Planning Stage), for Conversion of Gas Network for Up To 100% H_2 by 2030[168]

12.2 Germany - E.ON/H2HoWi Project - Conversion of existing NG pipeline to 100% H_2 (2020 - 2023)

In November 2020, German gas utility company E.ON[169] announced it was testing the technical viability of turning gas pipelines into 100% H_2 pipelines. The trial with 100% H_2, which is part of the H2HoWi development project, would consist of converting one existing, medium-pressure pipeline in Holzwickede in North Rhine Westphalia. The company referred to several trials that had already explored higher admixture rates, including a trial with up to 20% H_2 by E.ON/Avacon.

12.3 Germany - Hydrogen Pipeline Network (2024 - 2032)

The Pipeline Technology Journal (PTJ)[170] reported on October 23, 2024, that Germany's Federal Network Agency approved a groundbreaking H_2 pipeline network spanning over 5,617 miles (9,040 kilometers). According to the project details, approximately 60% of the pipelines will be repurposed from existing NG infrastructure, while the remaining portion will be completed with newly constructed pipelines by 2032. The project, which will receive $20.3 billion (€18.9 billion) from a consortium of 15 transmission system operators (TSOs), is expected to have a feed-in capacity of 101 GW and a feed-out capacity of 87 GW by 2032, making it the largest H_2 pipeline system in Europe.

The H_2 core network will be constructed in phases. The first H_2 conversion lines are expected to become operational in 2025. The Federal Network Agency will ensure that only NG pipelines no longer needed for NG transport are converted to H_2. In 2026, the Federal Network Agency is set to approve the first integrated network development plan.

12.4 U.S. – Hydrogen City, Texas (2022 - Present) – Green H_2 Hub with two new H_2 pipelines

Hydrogen City, TX, is an integrated green H_2 production, storage, and transport hub[171] being developed by Green Hydrogen International (GHI) (see Figure 82). It will harness up to 60 GW of solar and wind energy. The project's first phase is set to open in 2026, with approximately 2 GW of green energy production (280,000 tons/yr of green H_2). It is envisioned that the project size will increase to 60 GW.

The site is in South Texas and centered around the Piedras Pintas Salt Dome, which will store the H_2 before transporting the 100% H_2 via a 75-mile (121 km) pipeline to an NH_3 production facility and local off-takers in Corpus Christi, TX, and Brownsville, TX.

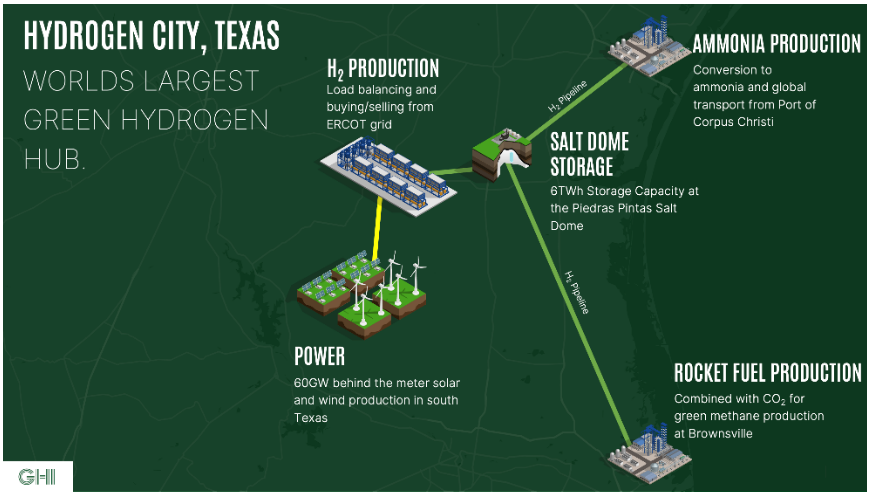


Figure 82. Green Hydrogen Hub in Hydrogen City, Texas[171]

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