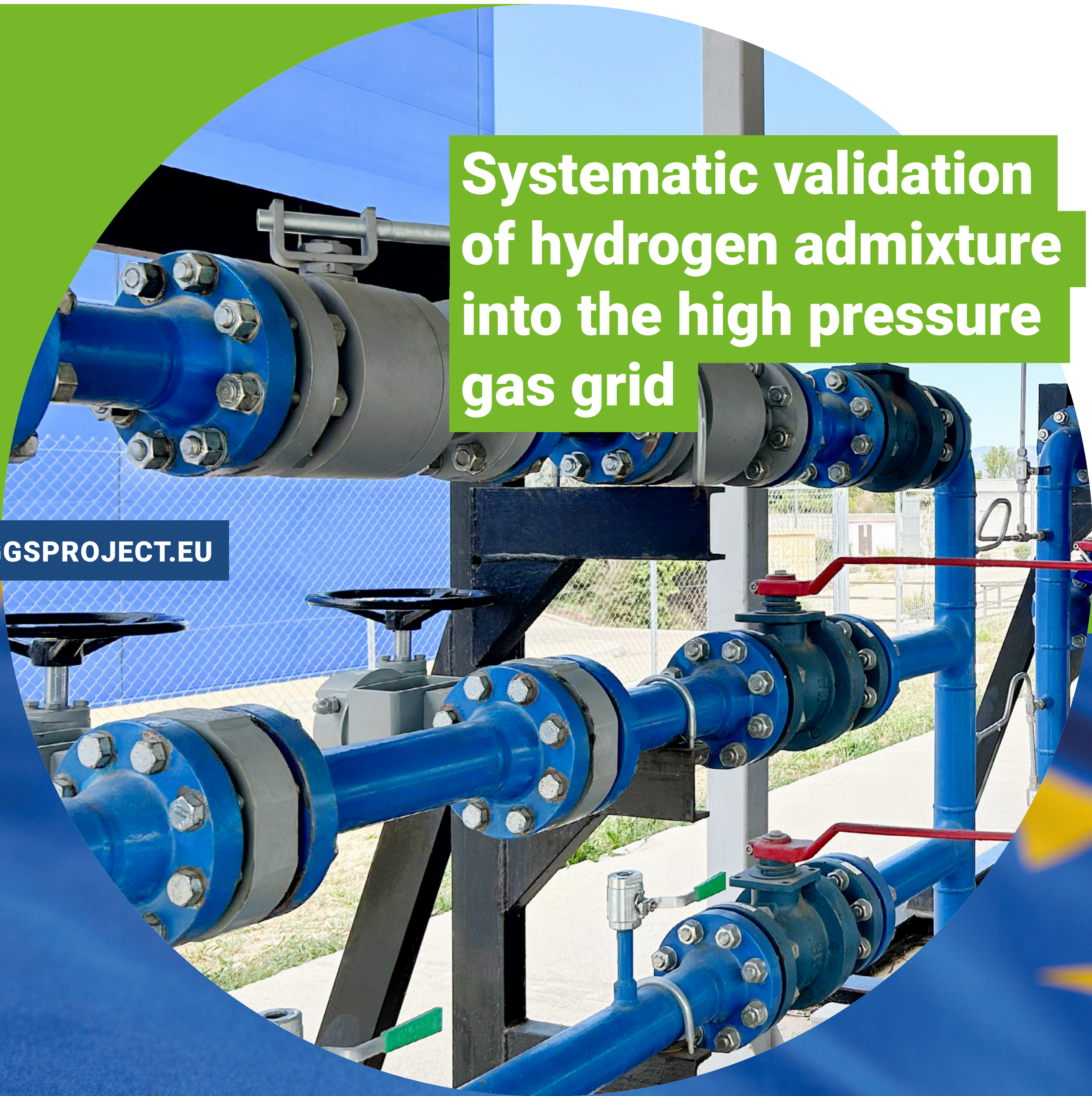
HIGGS

Hydrogen in Gas Grids

Systematic validation of hydrogen admixture into the high pressure gas grid



WWW.HIGGSPROJECT.EU

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No. 875091 'HIGGS'.
This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation program, Hydrogen Europe and Hydrogen Europe Research.

Clean Hydrogen Partnership

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Clean Hydrogen Partnership

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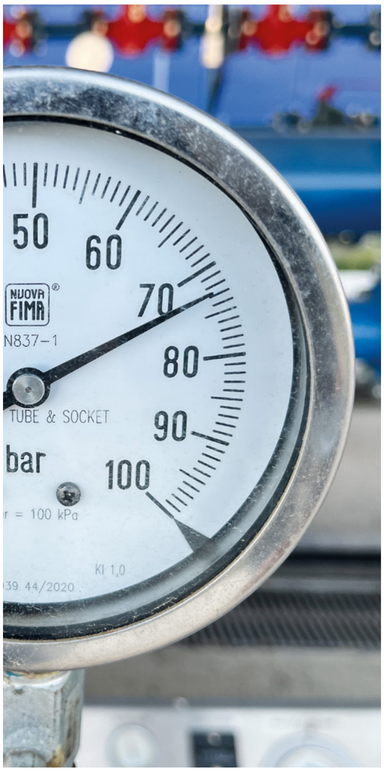

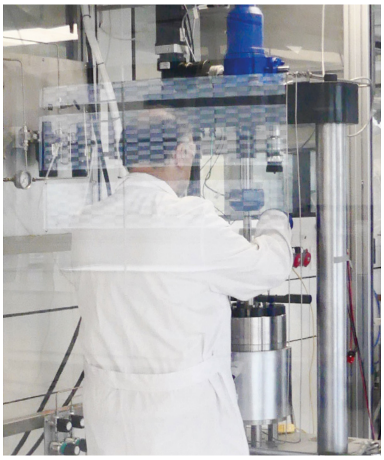

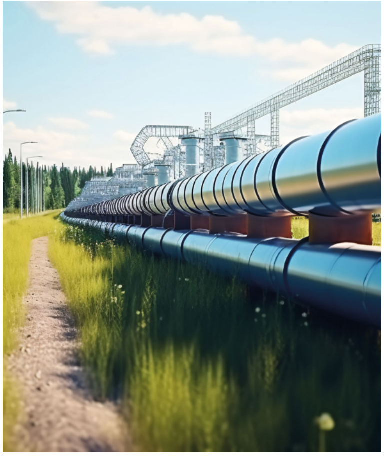

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1 Introduction

1.1 | Overview of the project and its objectives

HIGGS stands for "Hydrogen in Gas Grids" and was a project conducted to systematically validate the admixing of hydrogen into the high pressure gas grid. The project aimed to decarbonise the European gas grid by clearing the pathway for the admixture of hydrogen.

The HIGGS project had the goal to show that the safe injection of hydrogen into the European high pressure, transmission natural gas grid is a sustainable and long-term solution to decarbonise the energy system. Safeguarding the hydrogen injection, HIGGS was going to identify remaining weaknesses regarding H_2-Readiness and develop a pathway for a stepwise integration of hydrogen in the European gas network.

Thereby, the project investigated the impact that high levels of hydrogen could have on the gas infrastructure, its components and its management. The main tasks within the project were:

- Mapping of technical, legal and regulatory barriers and enablers for admixing up to 100% H_2 in the high-pressure gas grid
- Setting up and operating a testing platform reproducing all the components of a high-pressure network
- Testing and evaluating different accessories, appliances and innovations for various H_2/CH_4 admixtures
- Techno-economic modelling for H_2/CH_4 admixtures within the high-pressure gas grid and equipment

The main findings and assessments compiled in the project have been merged in the form of a document that describes a pathway to enable higher concentrations of hydrogen in the natural gas transmission grid. This pathway, among others, includes a list of potential issues, barriers and facilitators for transport and interoperability in the gas grids, proposals on regulations codes and standards, a summary of the recommendations for admixture and injection facilities as well as for the gas market and operation considerations.

In order to achieve the envisioned goals, the project team collected information on various key aspects regarding the integration of hydrogen in the high-pressure EU gas grid. Special emphasis was set on legal, regulatory and technical aspects by mapping the present equipment, as well as regulations, standards and certification (RSC) of the natural gas grids. The resolvement of these most critical RSC bottlenecks will not only enable end users and operators to operate the entire gas grid safely but also help to avoid the replacement of fully operable equipment and appliances due to rising hydrogen concentrations in the gas grid.

Statement of Dr. Vanesa Gil, project coordinator in HIGGS, ARAID Senior Researcher and Head of R&D at Aragon Hydrogen Foundation.

More about:

Interview with Dr. Vanesa Gil – Project coordinator – Aragon Hydrogen Foundation, 2023.
https://www.youtube.com/watch?v=0-LuB6G89Ak

1.2 | Importance of hydrogen integration in gas grids for decarbonization and energy transition

The European Union's ambitious climate targets aim to achieve net-zero greenhouse gas emissions by 2050, and the current global political situation encourages efforts to achieve energy independence in the EU by decreasing the use of imported fossil fuels. Both goals can be achieved by significantly increasing renewable energy production and storage, which requires efficient hydrogen production and storage correlated with the decarbonisation of the transport and industrial sectors. To achieve this, the EU has implemented plans and instruments to further support the hydrogen transition. One of this instrument is e.g. REPowerEU to additionally install at least 40 GW[a] of electrolysis capacity for renewable hydrogen by 2030.

As the EU addresses the urgent need to reduce greenhouse gas emissions, the integration of hydrogen (H_2) into existing gas grids has emerged as a promising strategy for achieving decarbonization and facilitating the transition towards a more sustainable energy landscape. Hydrogen, a clean and versatile energy carrier, holds immense potential to replace traditional fossil fuels, mitigate carbon emissions, and foster a low-carbon economy.

The integration of hydrogen into gas grids presents a transformative opportunity to decarbonize the gas sector. Natural gas, although associated with less GHG emissions and cleaner than other fossil energy carriers such as oil and coal, still has to be substituted with renewable or low-carbon gases to meet the European Green Deal goals. By blending hydrogen into natural gas pipelines, the carbon content of the gas mixture can be significantly reduced, thereby lowering overall emissions. It has been the working theses of the project that this blending can occur at varying ratios, with hydrogen percentages increasing over time as the necessary infrastructure and technology advancements are realized. This transition offers a bridge between the current fossil fuel-based energy system and a cleaner, hydrogen-based future.

One more aspect of hydrogen integration is its potential to act as a storage medium for excess renewable energy. Solar and wind powered renewable energies are intermittent energy sources, and their fluctuations can strain electricity grids. Excess renewable energy can be used to electrolyze water and produce hydrogen through a process called Power-to-Gas (PtG). The produced hydrogen can then be stored in existing gas infrastructure, serving as a form of energy storage. During periods of high demand or low renewable generation, this stored hydrogen can be reconverted into electricity or heat, providing grid stability and flexibility.

Certain sectors, such as heavy industry and long-haul transportation, face significant challenges in transitioning to low-carbon alternatives. Hydrogen, especially when produced from renewable sources or combined with carbon capture and storage (CCS) technologies, holds promise in addressing these challenges. Hydrogen can serve as a feedstock for industrial processes like steel and ammonia production, and it can power fuel cell vehicles or be used in internal combustion engines for long-distance transportation.

While the potential of hydrogen integration in gas grids is significant, some challenges remain. One of the main challenge today is the lack of specific regulations and standards regarding the injection of hydrogen into natural gas networks. Additionally, ensuring the production of low-carbon or renewable hydrogen at scale is essential for realizing the full environmental benefits.

[a] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en

1.4 | Project Partners

Fundación para el Desarrollo de las Nuevas Tecnologías del Hidrógeno en Aragón (FHA)

FHa is a private, non-profit research center that has been boosting hydrogen as an energy source since 2003. The initiative was promoted by the regional Government of Aragon and initially supported by 28 key entities from various sectors of the Aragonese economy. With continuous backing, it now celebrates its 20th anniversary, boasting a board of trustees exceeding 90 members. Focused on integrating Aragon into the global hydrogen economy, its objectives include fostering employment and wealth through strategic projects, establishing a collaborative industrial network for sustainable energy ventures, and implementing a comprehensive regional strategy outlined in its pioneering Hydrogen Master Plan, now in its fourth edition since 2007.

Within the project FHa was responsible for the project coordination and administrative tasks. Additionally FHa had a technical role in two work packages, focusing on the design, construction, and operation of the hydrogen admixing test platform, including the testing of different gas grid components. FHa also assisted with research on the potentials of hydrogen injection in the EU.

www.hidrogenoaragon.org

German Technical and Scientific Association for Gas and Water (DVGW)

DVGW – German Technical and Scientific Association for Gas and Water has been working for the gas and water industry as an independent and unbiased technical scientific association since 1859, the objective being to create a basis for the safe and technologically flawless supply of gas and water. It is the reference German institution for the development of technical rules, the associated pre-normative research and certification of gas and water related appliances. Regulations merely constitute the basis of the services the DVGW has to offer its members. The practical work in the gas and water sector is based on the technical rules of DVGW. The association has excellent laboratories for the testing of gas related processes, an unbiased view on renewable gases, power to gas and related technologies.

DVGW led two work packages, one on legal, regulatory and technical aspects and one on a pathway towards integrating hydrogen in European gas networks. Herein, DVGW focused on mapping the current state of regulations, codes and standards (RCS) and on a technical inventory of high pressure gas grids, providing updated information on pre-normative research activities. Furthermore, DVGW elaborated the set of recommendations towards integration of higher levels of hydrogen in the EU and assisted with the design of the test platform.

www.dvgw.de

European Research Institute for Gas and Energy Innovation (ERIG)

ERIG is a European research and development network that guides gas in the transition process towards a future renewable based energy system. It is a non-profit network for European cooperation in research and innovation in the field of sustainable and innovative gas technologies and the use of natural gas with renewable energies. ERIG members represent national technical and scientific gas organizations and associations that represent in particular the new requirements of energy and gas in Europe.

The research portfolio of ERIG members covers all aspects from the production of gas through to gas utilization in different markets.

Within the project ERIG was responsible for the work package "creating impact", which included communication and dissemination of project activities and results as well as network activities to transfer gained knowledge.

www.erig.eu

Tecnalia
TECNALIA is a benchmark research and technological development centre in Europe; with 1,400 experts from 30 different nationalities, focusing on transforming technology into GDP to improve people's quality of life, by creating business opportunities for companies. Its main scopes of action are: digital transformation, advanced manufacturing, energy transition, sustainable mobility, urban ecosystem and health.

TECNALIA led the work package on the validation of components and materials based on conducted experiments. Herein TECNALIA relied on their experience in determining and performing the most relevant lab scale artificial ageing cycle tests and coating characterizations. Characterization of samples were performed according to a variety of international standards. Additionally, TECNALIA manufactured and test hydrogen purification membranes at lab-scale, and designed and commissioned a hydrogen purification prototype.

www.tecnalia.com/en

Eastern Switzerland University of Applied Sciences (OST)
OST is the university of applied sciences for the six cantons of Eastern Switzerland and the Principality of Liechtenstein. It is the region's educational hub, with around 3,800 students in six departments, 1,500 professionals in executive education, and more than 1,000 ongoing research projects. OST brings together 170 years of tradition in education and research.

The Institute for Energy Technology IET is part of the Department of Technology at OST.IET's core competences lie in the power-to-x technology and it is the leading Swiss research institution for applied power-to-x topics. The IET leads national and international projects, it offers consultancy services for the local industry and it operates a 25 kW pilot and demonstration plant including methanation and grid integration.

Within the project, OST led the work package on techno-economic modelling of hydrogen admixing into the European gas grids with a focus on enablers and interoperability and on an assessment of the gas separation technology.

www.ost.ch/en

Redexis
Redexis is an integrated energy infrastructure company that is active in the development and operation of networks for the transmission and distribution of natural gas, the distribution and sale of liquefied petroleum gas and the promotion of new gas-powered mobility infrastructure, renewable gas and hydrogen. With 769,995 connection points, Redexis operates 12,058 kilometers across ten autonomous communities, providing Spanish homes, businesses and industries with access to new, more sustainable and efficient energy sources.

REDEXIS provided background information and feedback for the high-pressure gas grid operation. They selected critical equipment and infrastructure and contributed to the technical design of the testing platform. Additionally, they supported the development of baseline cases for techno-economic modeling and collaborated on defining recommendations. REDEXIS also focused on addressing interoperability, grid management, and cross-border issues.

www.redexis.es

2 Systematic and Experimental Validation of Gas Grid Components

2.1 | The sensitivity of gas grid components towards hydrogen

Assessing the compatibility of components and materials within the natural gas grid when introducing hydrogen is a critical task. Hydrogen is emerging as a promising energy carrier and a key player in the transition towards a cleaner, more sustainable energy future. As we strive to reduce carbon emissions and increase the integration of renewable energy sources, hydrogen injection into the gas grid offers a potential solution. However, ensuring the seamless integration of hydrogen into existing natural gas infrastructure is of high importance.

First and foremost, safety is a concern that is often publicly addressed. Hydrogen behaves differently from natural gas and poses unique challenges. It is highly reactive, and its smaller molecule size could lead to permeation through materials that are otherwise impermeable to methane. This could result in material embrittlement and potentially system failures. Assessing compatibility is essential to prevent leaks, explosions, and other safety hazards that could occur. Therefore, integrity and reliability of the gas grid must be upheld. The natural gas grid is a complex network of pipelines, valves, compressors, pressure regulators and flow meters, among other components. Over time, exposure to hydrogen may cause embrittlement in these materials. A thorough assessment ensures that the structural integrity of the grid is maintained, reducing the risk of infrastructure failures that could disrupt energy supply and incur significant repair costs.

Economic considerations also come into play. The transition to hydrogen-enriched gas grids may involve substantial investments. Failing to assess compatibility can result in premature component replacements and system retrofits, which can be costly. By conducting compatibility assessments upfront, operators can make informed decisions about materials and components, minimizing the financial burden associated with the transition.

Environmental benefits are another important factor. Hydrogen, when produced from renewable sources, is a clean-burning fuel that can help reduce greenhouse gas emissions. However, if the introduction of hydrogen into the gas grid leads to leaks or other issues due to material incompatibility, it can inadvertently contribute to emissions and compromise its environmental benefits. Compatibility assessments ensure that the environmental advantages hydrogen injection into gas grids are maximized.

Public perception and acceptance are crucial aspects as well. Trust in the safety and reliability of the gas grid is important for both consumers and investors. Any incidents related to the introduction of hydrogen could erode this trust. By thoroughly assessing compatibility and implementing appropriate safety measures, the industry can build confidence in the hydrogen transition.

Finally, technological advancements play a role. As research continues into better materials and technologies for hydrogen transport and storage, ongoing compatibility assessments help identify and integrate these innovations into the grid. This ensures that the gas grid remains adaptable and can harness the full potential of hydrogen as an energy carrier.

2.2 | HIGGS's systematic approach to testing and evaluating grid components

The HIGGS consortium investigated the risk of hydrogen embrittlement and gas leakages as potential concerns when repurposing the natural gas grid for hydrogen service, particularly given the high pressures at which the transport grid operates. Consequently, a dedicated testing facility has been established as part of the project's experimental approach to evaluate the performance of materials used in the pipelines, valves, and a wide array of components and equipment within the grid concerning their compatibility with hydrogen.

Figure 1: Picture of the dynamic (left) and static (right) sections of the testing platform

The R&D facility comprises an integrated system consisting of an admixture system, a testing platform, and a gas separation prototype. It has been meticulously designed with the capability to inject more than 5 kg/h of hydrogen at 80 bar pressure, aimed at gathering crucial insights into the impact of hydrogen on equipment within the transmission gas network and addressing deblending challenges in the recovery of injected hydrogen for end-use applications. This R&D facility has been thoughtfully designed and equipped to evaluate the compatibility of materials and components with hydrogen within the context of transmission gas grids. It offers the ability to conduct a wide range of tests under realistic conditions, ensuring that the transition to hydrogen-based energy systems in these grids can be made with confidence in terms of safety, performance, and efficiency.

The admixture system is responsible for generating gas atmospheres for the experiments conducted at high pressures, offering blends with hydrogen content ≤ 30 mol%, but also adding the possibility for tests under 100% hydrogen. This is achieved through a series of flow controllers and pressure regulators, ensuring precise preparation of gas blends at lower pressures. Subsequently, the admixture is compressed to a maximum of 200 bar and stored in a pressurized buffer, which serves as a feed for various components of the testing platform, such as the gas injection system.

Within the testing platform, representative components commonly found in transmission grids are included, along with pipes made of different API 5L steel grades. The platform is divided into two distinct sections:

- **Static Section:** In this section, assessments were conducted on leakages and hydrogen permeation in components (valves of varying types and couplings, such as threaded joints and flanges). These evaluations were carried out under a constant pressure of up to 80 bar, mirroring conditions found in transmission gas grids. In the static section, gas did not flow continuously. Instead, the lines are pressurized, sealed, and subsequently monitored for pressure drop and gas quality throughout the tests.

- **Dynamic Section:** Contrasting the static section, the dynamic section introduces a continuous gas flow through various branches within a closed-loop system. This is achieved by employing a compressor and a pressure regulator to create the required pressure difference within the setup, serving as the driving force for the experiments. The dynamic section features a range of steel grades and incorporates typical components found in transmission gas grids, including filters, flowmeters, and flow regulators. The steel grades considered in these tests span from API 5L X42 to X70. The materials were introduced both as newly welded pipes and strained specimens and were placed inside a pig trap for exposure to high-pressure hydrogen environments.

When hydrogen is transported as part of a blend within the natural gas transport grid, there is a potential scenario where certain end-users, with stringent requirements for the quality of natural gas, may not be equipped to directly utilize such a blend. In such cases, they may require a preliminary purification process. Membrane technology emerges as a viable solution for this purification step, and the HIGGS project has taken this into account within its experimental campaign. This involved the integration of a gas separation prototype to investigate the feasibility of recovering hydrogen from methane in high-pressure blends.

The HIGGS membrane prototype served the purpose of separating hydrogen from a gas mixture comprising both hydrogen and methane, at high pressures, with the capability to operate at pressures of up to 80 bar. The process yields two distinct product streams: i) Permeate: This stream consists of the gas that successfully passes through the membrane, resulting in high-purity hydrogen, delivering it at a lower pressure compared to the original feed gas. ii) Retentate: This is the gas stream that does not permeate through the membrane. It retains the same high-pressure conditions as the initial feed gas but typically contains methane with a reduced hydrogen content.

Figure 2: Gas separation prototype

More about:

"Hydrogen in Gas GridS – Test-Platform to examine the effect of H_2 on gas grid components and steels", 2023.
https://www.youtube.com/watch?v=ob0FSIfyt3A

The kind of tests performed in HIGGS to analyse the impact of hydrogen on the transmission gas grids were the following:

1. Gas tightness tests

These tests are conducted within the static section of the testing platform to investigate the potential occurrence of hydrogen leakages in valves and couplings when they operate at high pressures, specifically at 80 bar, with hydrogen blends and pure hydrogen (100%). The testing procedure involves pressurizing the pipelines containing these components with the designated gas blend and subsequently maintaining these lines in a sealed state. Over time, pressure levels are monitored continuously, and the gas composition within the lines is periodically analyzed using gas analyser. These tests are designed to detect any instances of gas leakage or the preferential permeation of hydrogen over methane.

The outcomes of these tests yielded valuable data in the form of pressure profiles and gas composition profiles over time. These profiles provided essential insights into the behavior of valves and couplings when exposed to high-pressure hydrogen blends, helping to identify potential issues and ensure the safe and reliable operation of the gas grid.

2. Constant displacement tests with API 5L steel specimens

HIGGS has undertaken a comprehensive study to assess the sensitivity of carbon steel pipes to hydrogen exposure. Notably, the project has focused on API 5L Grades X42, X52, X60, and X70, which are considered among the most representative grades commonly encountered in European transport grids. To investigate the potential effects of hydrogen on these materials, the project employed specially machined constant strain specimens. These specimens were subjected to high-pressure hydrogen exposure as part of the study. Three normalized constant displacement tests have been used:

- **C-Ring Specimens:** C-ring specimens are particularly suitable for making transverse tests from tubular products and are subjected to bolt loading to attain the desired stress level. This stress level is expressed as a percentage of the material's yield strength typically falling between 75% and 100% of the elastic limit. Standards such as ISO 7539-5 and ASTM G38 provide guidelines for the fabrication and stressing of C-ring samples. The susceptibility of hydrogen embrittlement with C-ring specimens is usually assessed by measuring the time it takes for cracking to occur during testing. These tests yield either a failure or no failure result. The addition of a notch generally made the specimens more sensitive to hydrogen embrittlement. In HIGGS project notched and unnotched C-ring test specimens were used.

- **4-Point Bend (4pb) Specimens:** Four-point bend specimens are usually flat strips of metal of uniform thickness, except when assessing welded specimens with one surface in the as-welded state. In the 4-point bend test, the specimen is subjected to constant tension by being supported on two loading rollers while a load is applied through two additional rollers. As with C-ring tests, deflections are limited to stresses below the material's elastic limit, generally ranging from 75% to 100% of the elastic limit. The evaluation of material resistance to the environment involves a visual inspection of the tested specimen in the tensile-stressed region to detect cracks, often aided by optical or scanning microscopies.

- **Precracked Fatigue Compact Tension (CT) bolt loaded Specimens:** These specimens are subject to a constant load and incorporate a device, such as a taper pin, to create a constant displacement at the loading points, resulting in wedge opening load (WOL) specimens. WOL specimens can be used to measure crack growth rate or simply observe crack growth. In the HIGGS project, fatigue precracked WOL specimens, machined from both the parent and welded metal, have been used for the loop experimental platform. Afterthe exposure period, the length of the crack is measured. The preparation and use of precracked specimens for tests under constant displacement are described in standards ISO 7539-6 and ISO 1114-4-Method C.

- The constant displacement steel specimens used in the study were subjected to hydrogen exposure in the dynamic section of the testing platform. Within this section, a specialized pig trap was installed, effectively serving as an autoclave for conducting the tests. This pig trap offers a controlled environment where the specimens can be securely placed for the duration of the tests.

- The operational process involves filling the pig trap with gas at a pressure of 80 bar, and maintaining it throughout the testing period. In the context of the HIGGS project, these specimens were exposed to this hydrogen-rich environment for a minimum duration of 2,000 hours. This extended exposure period allows for a comprehensive assessment of the materials' behavior and their response to high-pressure hydrogen conditions, facilitating a thorough understanding of their performance in real-world applications within the gas grid.

Figure 3: Insertion of strained specimens in the pig trap

As a complement to the constant displacement test specimens the Slow Strain Rate Test (SSRT) method was used for the evaluation of hydrogen embrittlement sensibility of the API 5L steels under study. The SSRT is a particularly important screening method to measure susceptibility to hydrogen embrittlement. Specimens were tensile strained to failure with "slow" strain rates, commonly in the range $10^{-6} – 10^{-4}$ s^{-1}. The results of the SSRT are evaluated comparing the results obtained in an inert environment (air/ N_2) and in hydrogen gas. The reduction of area ratio (RRA) and the notched tensile strength ratio (RNTS), are used as a measure of hydrogen susceptibility in smooth or notched specimens, respectively. Fracture surface analyses are carried out by scanning electron microscopy (SEM) to determine features of hydrogen embrittlement.

In HIGGS, SSRT was conducted using notch tensile specimens. This will allow to precisely localize the failure in the base or weld zones. A minimum of two tests was conducted in 100% H_2, at a test pressure of 80 bar and using a strain rate of $3.6 \times 10^{-5} s^{-1}$, following ASTM G142 and ASTM G129 standards.

Figure 4: SSRT tensile, fracture and fatigue machine for testing in H_2 gas

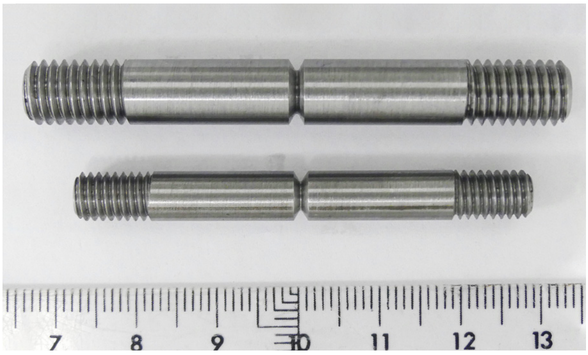


Figure 5: Notched round specimens for SSRT. Base (up) and welded (down) specimens from X70 steel grade

3. Sensitivity of valves and equipment towards hydrogen

The HIGGS project went beyond assessing just the materials of pipes; it also considered the impact of hydrogen on valves and various equipment components. Valves of the different types installed in the static section of the testing platform, including butterfly, plug, or ball valves with either threaded or flanged couplings, were subjected to exposure to hydrogen and hydrogen blends at a high pressure of 80 bar for a minimum duration of 2,000 hours. Upon completing the tests, the valves were meticulously disassembled, and all of their components underwent a thorough inspection to identify any signs of hydrogen-induced damage.

Equipment within the dynamic section of the testing platform, which included filters, pressure regulators, and flow meters, were subjected to a parallel methodology. At the conclusion of the tests, this equipment was disassembled, and each of its individual parts was examined with the assistance of a stereo microscope equipped with a camera. This detailed inspection aimed to detect any instances of cracking or other forms of hydrogen-related damage, such as blistering.

By comprehensively evaluating the effects of hydrogen exposure on valves and equipment components, the HIGGS project contributed to a holistic understanding of the compatibility of various elements within the gas grid when exposed to hydrogen, ensuring safety and reliability in the transition to hydrogen-based energy systems.

4. Gas separation test with membrane technology

Membrane technology has played a crucial role in the HIGGS project, primarily focusing on H_2/CH_4 separation. Specifically, Pd(Palladium)-based double-skinned membranes were meticulously deposited onto porous ceramic tubes and subsequently integrated into the membrane prototype for this study. The selection of Pd-based membranes stemmed from their exceptional attributes, notably their high hydrogen permeance and selectivity, surpassing other available materials. The gas separation prototype consisted of three distinct sections:

1) Feed Section: This segment was responsible for delivering the gas blend, which was prepared in the admixture system of the R&D platform, to the membrane module at high pressure.
2) Membrane Reactor: Within this component, the Pd-based membranes were strategically positioned, and an operating temperature of 400 °C is maintained using an oven.
3) Analysis Section: This part of the prototype is designed to assess the composition and quantity of the separated gas flows.

The prototype itself comprised an inlet, serving as the feeding line, and two outlets: permeate and retentate. The permeate stream is enriched with hydrogen, while the retentate stream carries a higher methane concentration. To regulate the trans-membrane pressure difference, a back-pressure regulator is strategically placed at the outlet of the retentate side. Both the retentate and permeate lines were seamlessly connected to the analysis section, which features mass flow meters for precise measurement and monitoring of the permeate and retentate flows. These flows was subsequently analyzed using a gas analyzer.

The prototype has undergone testing using two distinct Pd-based membranes, exclusively with 20/80 % H_2/CH_4 blends and without impurities. In the initial experiment, the long-term stability of these membranes was assessed under a constant feed flow and feed pressure of 80 bar. In a subsequent series of tests, the feed pressure was systematically varied (10, 20, 40, 60, 80 bar), and the feed flow was adjusted to achieve the maximum hydrogen recovery for each specific feed pressure setting.

Figure 6: Gas separation prototype developed during HIGGS

2.3 | Key findings and insights from experimental validation

The experimental campaign conducted encompassed testing under four distinct gas compositions, all maintained at a pressure of 80 bar. These compositions comprised hydrogen blends with methane and 100% hydrogen. The hydrogen blends in some cases contained trace impurities of H_2S and CO_2, which are the primary pollutants typically encountered in natural gas streams:

- **20 mol % H_2 in CH_4**
- **20 mol % H_2 in CH_4 + H_2S + CO_2**
- **30 mol % H_2 in CH_4 + H_2S + CO_2**
- **100 mol % H_2**

Regarding the tightness of valves in relation to hydrogen, it's noteworthy that, for all the tested valves, the P/Z·T relationship (pressure/temperature relationship corrected by the compressibility factor of hydrogen or the hydrogen blend) remained relatively constant throughout the tests, regardless of the hydrogen content in the gas. Additionally, the hydrogen concentration within the lines generally remained stable during the testing process. Similar findings were observed with both screwed and flanged couplings. In both cases, the behavior regarding gas leakage remained consistent with what was previously observed.

However, it's worth mentioning that some minor leaks were detected in the case of screwed ball valves, primarily due to internal gas leakage. Notably, when a leak occurred, it involved the entire gas blend escaping, and there was no preferential leakage of hydrogen over methane.

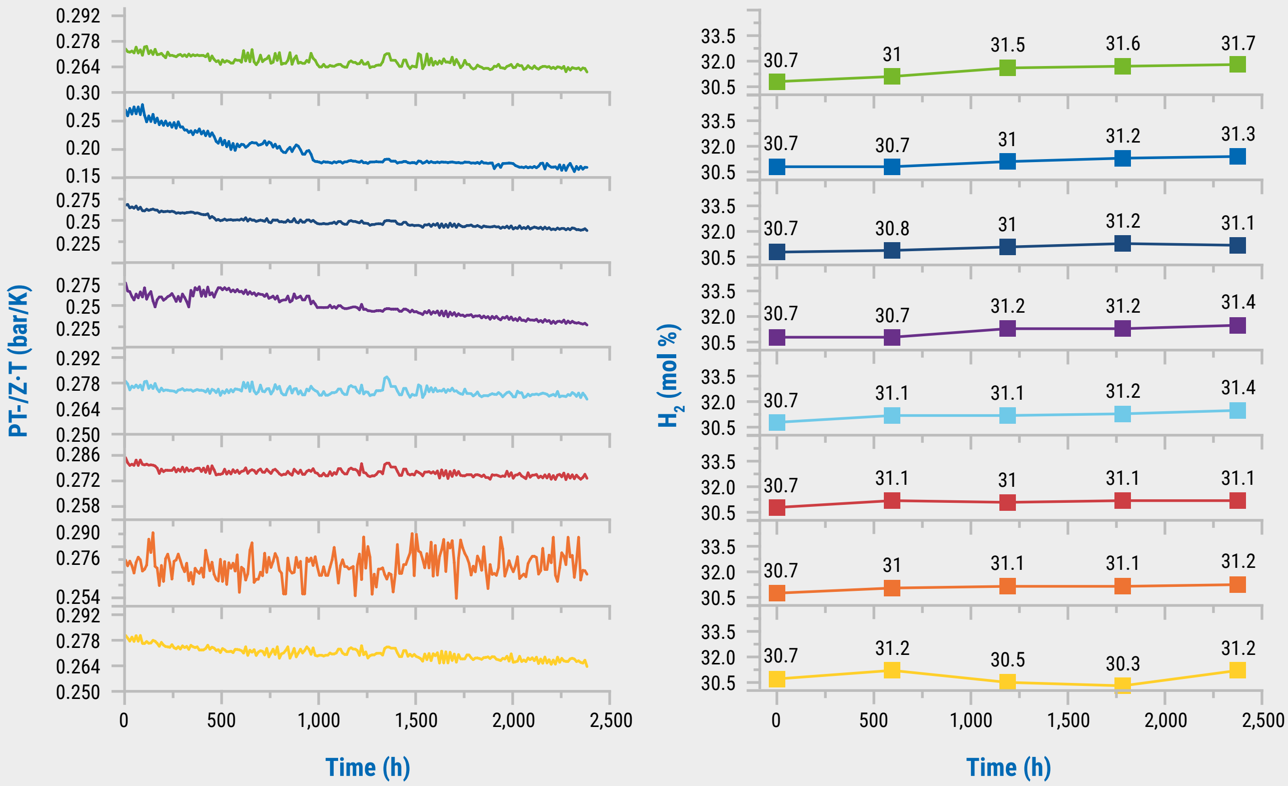


Figure 7: Results of gas tightness tests

In the case of potential embrittlement phenomena in carbon steel pipes, it's noteworthy that no damage was detected in any of the constant displacement steel samples, neither on the base material nor in the welded joint, irrespective of the concentration of hydrogen present in the high-pressure gas during the tests.

Detailed metallographic sectioning confirmed the absence of cracks in both the base and notch C-ring samples. Similarly, in the 4pb specimens, metallographic sectioning validated the absence of cracks in the base, heat-affected zones (HAZ), and weld metal areas.

For the CT specimens, a specific procedure was followed. These specimens were unloaded (by removing the bolt) and then subjected to heat tinting (for 30 minutes at 300 °C) before being broken. This procedure aimed to evaluate whether the initial fatigue pre-crack (generated in air before exposure to the hydrogen blend) exhibited any growth. The fracture surface was meticulously examined by SEM. Measurements of the crack front extent were taken at three positions. Importantly, no hydrogen-induced crack growth was measured for any CT-WOL specimen, with crack propagation being less than 0.25 mm. Furthermore, the examination of the fracture surface revealed a consistent fracture mode in both the fatigue pre-crack and the crack front, affirming the absence of hydrogen-induced damage.

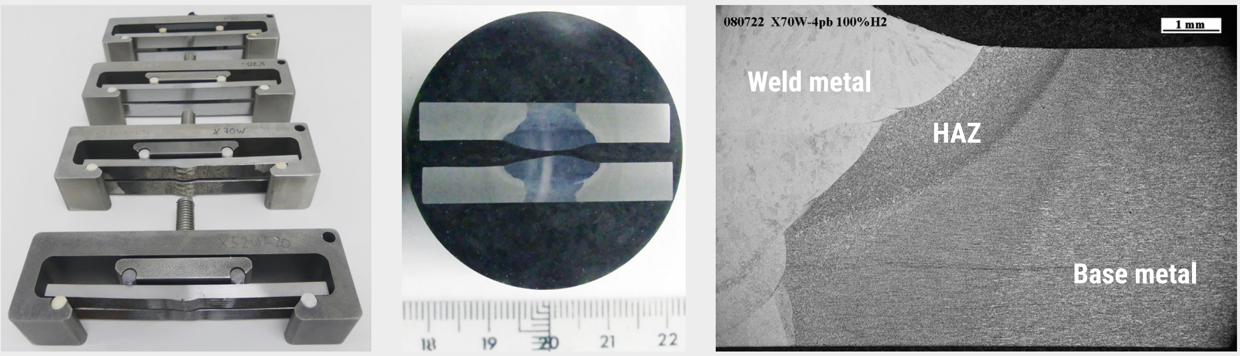


Figure 8: 4pb specimens after the 100% hydrogen campaign (left); detail of embedded cross sections (center); optical micrograph of X70 welded 4pb cross sections after the 100% hydrogen campaign (right)

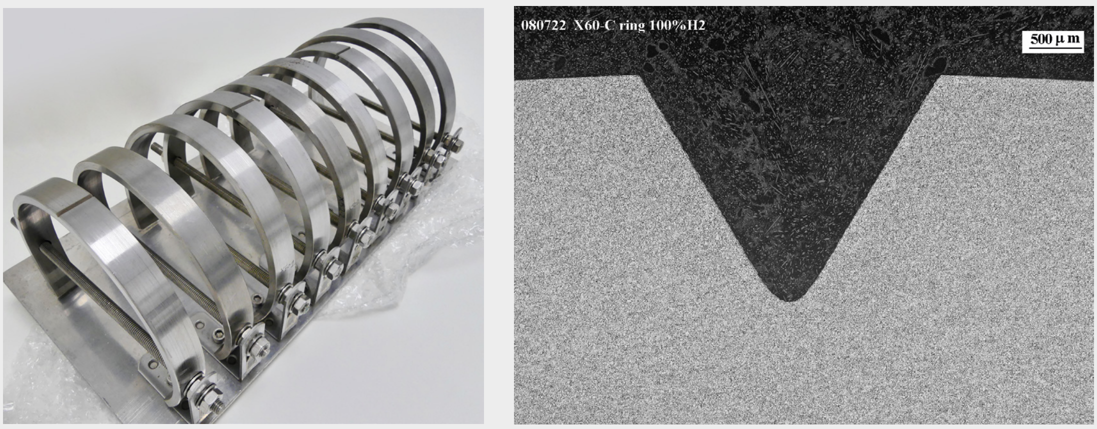


Figure 9: C-ring specimens after the 100% hydrogen campaign (left);
Optical micrograph of notched C-ring cross section from steel grade X60 after the 100% hydrogen campaign (right)

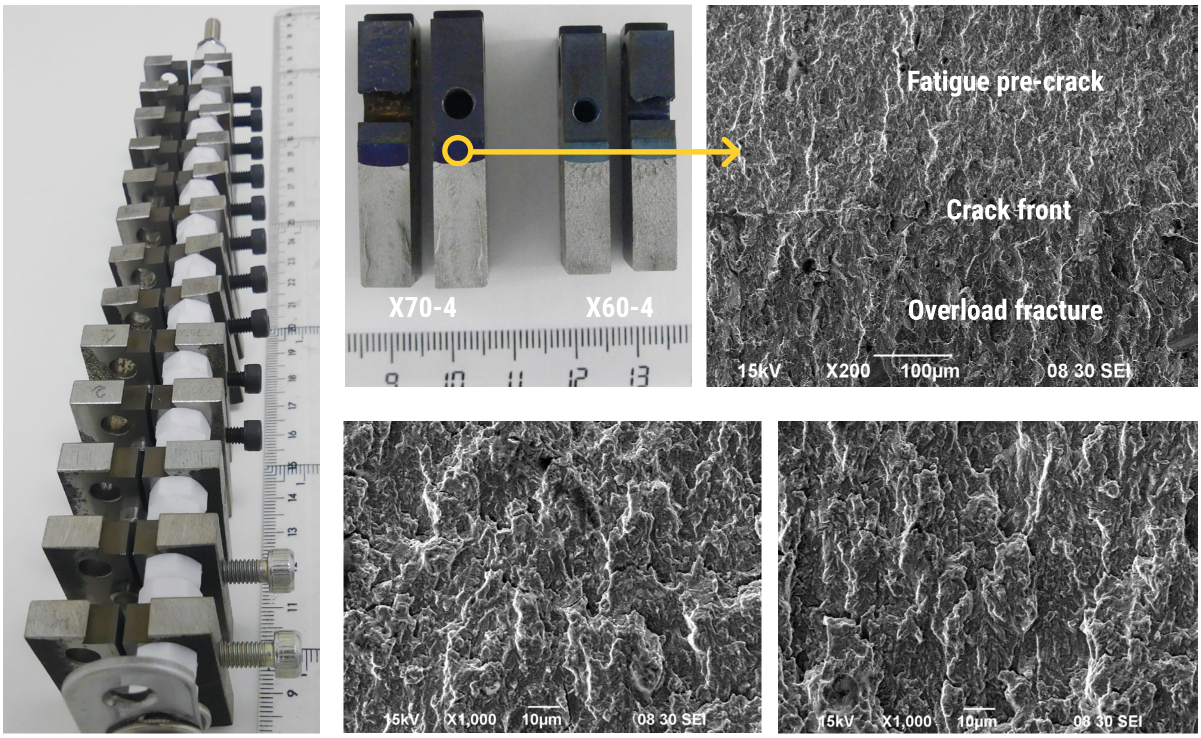


Figure 10: Rack with tested CT-WOL specimens after the 100% hydrogen campaign (up-left); detail of unloaded, heat tinted (300 °C) and broken CT-WOL specimens (up-centre); SEM micrograph of the fatigue fracture surface showing detail of the crack front (up-right); SEM micrographs showing detail of the fracture surface close to the crack front (down-left) and approximately 1mm from the crack front (down-right)

When scrutinizing the potential damage that hydrogen may have inflicted on the principal components of valves and equipment, it's important to note that, aside from linear or scratch abrasions in some components, primarily caused during the disassembly process, there were no distinct indications of hydrogen-induced damage observed on the various inspected parts. The only notable exception was the emergence of blistering phenomena, which was identified exclusively on the seat of the pressure regulator when exposed to hydrogen concentrations exceeding 30 mol %. No blistering was observed for this component when testing it in an atmosphere of 100 mol% hydrogen. It is not excluded, that the observed blistering may be due to a previous defect in the pressure regulator seat.

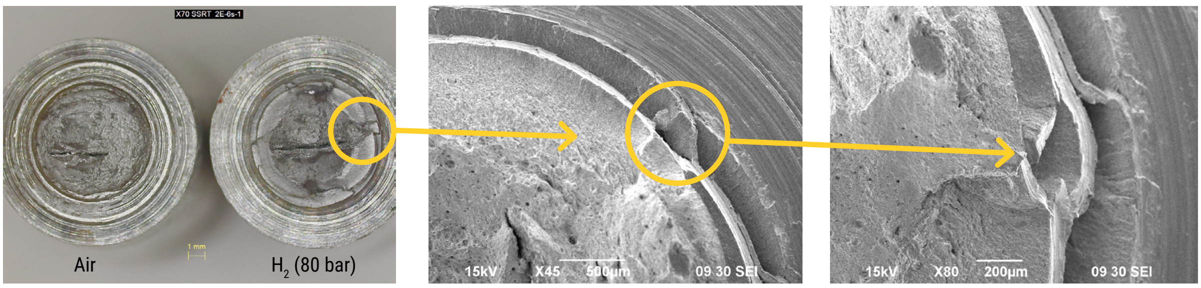


Figure 11: Fracture surface of notched SSRT x70 specimens tested in air and in H_2 (80 bar)

Finally, the gas separation tests conducted with the membrane prototype have yielded highly promising results in a 500h long test. The separation of the 20/80 (mol %) H_2/CH_4 blend was successfully achieved using Pd-based membranes. The prototype consistently generated a stable permeate flow rich in hydrogen, with a minimal concentration of 98.0 mol%. By adjusting the feed flow and feed pressure conditions, this hydrogen-rich permeate stream could be further enhanced to reach concentrations ranging from 99.5% to 99.8 mol%. These findings demonstrate the effectiveness of the membrane technology in efficiently separating hydrogen from methane, offering a viable pathway for producing high-purity hydrogen streams for various applications.

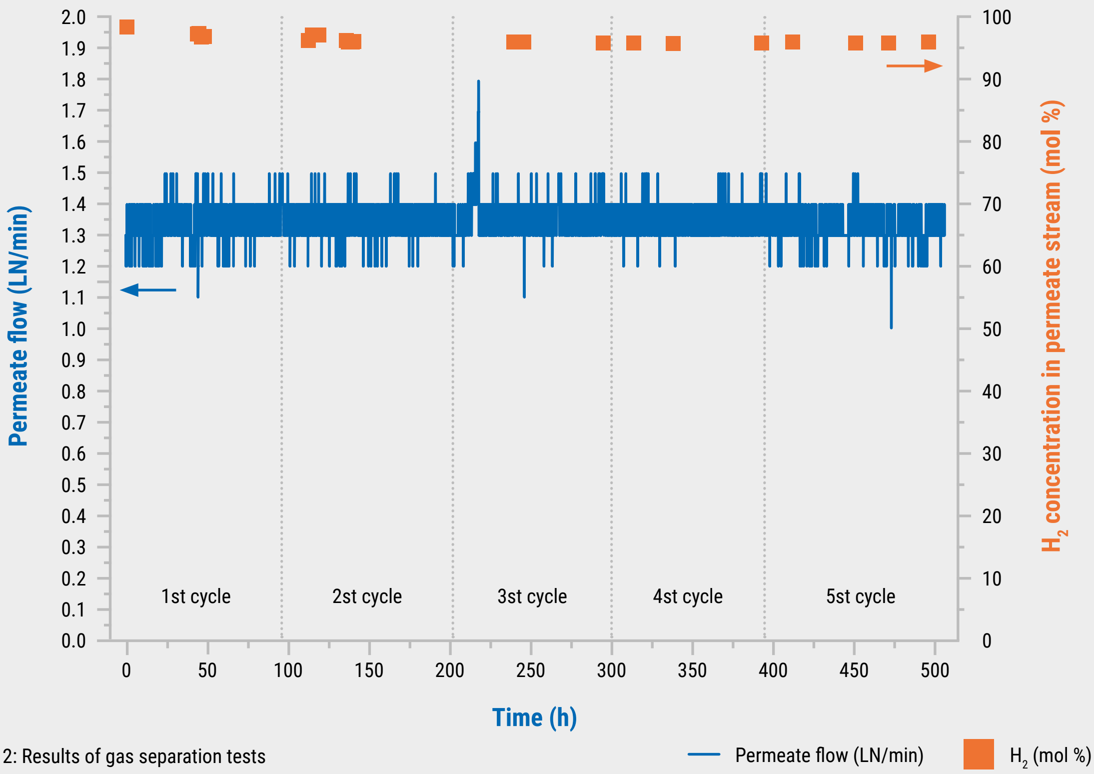


Figure 12: Results of gas separation tests

More detailed insights regarding the material testing can be found in the following deliverables:

D4.2 Report on results of the validation:
https://higgsproject.eu/d4-2-report-on-results-of-the-validation

The final results of the experiments in D4.4 are currently undergoing finalisation (as of November 2023). They will be published and available under the following link in January 2024.

D4.3 Update of the status of the ongoing experimental campaign:
https://higgsproject.eu/d4-3-update-of-the-status-of-the-ongoing-experimental-campaign

D4.4 Final report on systematic validation of the experimental material testing campaign:
https://higgsproject.eu/d4-4-final-report-on-systematic-validation-of-the-experimental-material-testing-campaign

2.4 | Recommendations for hydrogen integration from a material point of view

Considering material compatibility and the prevention of potential leaks are crucial factors to consider when repurposing the natural gas grid for hydrogen use. Hence, it is imperative to conduct tests in relevant environments to certify materials for hydrogen service. Nevertheless, this approach is challenging due to the absence of regulations governing such certifications, which is one of the main barriers identified in HIGGS.

During the tests carried out in HIGGS, no instances of hydrogen embrittlement or other types of damage resulting from hydrogen exposure were observed. This suggests that the most commonly used pipe materials appear suitable for hydrogen service. However, more in-depth research is essential to comprehend how these materials behave in the presence of hydrogen. Performing this research using standardized procedures is vital to facilitate material certification and, consequently, ensure the readiness of gas grids for hydrogen transportation.

3 Technoeconomic Validation and Modelling

3.1 | Interview with the work package leader – Salvatore Oricchio

Could you provide an overview of the HIGGS project and your role as the Work Package Leader for the techno-economic modeling of hydrogen injection into EU gas grids (WP5)?

HIGGS aimed to find out to what extent and under what circumstances hydrogen can be added to the existing gas grid. Various aspects such as materials, costs and legal framework conditions were taken into account at the transmission level.

As work package leader, I am responsible for modelling and calculating natural gas/hydrogen blends. To this end, we were investigating how and to what extent an existing natural gas grid could be converted depending on the hydrogen content and what consequences this would have on parameters such as transport costs or the energy transported.

Salvatore Oricchio
WP5 Leader, Researcher at IET Institute for Energy Technology – Eastern Switzerland University of Applied Sciences (OST)

In regard to baseline, assumptions and scope of the modelling, what were the key findings regarding the consumption of natural gas and hydrogen in Europe up to 2050, and how do they influence greenhouse gas emissions.

We've observed that the European natural gas supply grew by 50% since 1990, leveling off at a lower point, while global consumption doubled. Over the past decade, Europe has seen a decline in gas demand. Most forecasts suggest a significant drop in natural gas demand by 2040 and 2050, driven by greenhouse gas reduction goals, including energy efficiency improvements, electrification, technology advancements, and societal behavior changes. In some cases, there may be a short-term rise in natural gas demand, like when gas-fired power generation replaces coal or nuclear power.

Even small hydrogen blend levels could absorb excess renewable energy, making it accessible to various end-users through suitable separation technologies.

This blending process significantly reduces greenhouse gas emissions, with a 20% hydrogen blend reducing CO_2 emissions by about 7%, increasing to 17% at 40% hydrogen content, and 31% at 60%.

D5.1 – Baseline, assumptions and scope for techno-economic modelling of hydrogen admixture into the gas grid

https://higgsproject.eu/d51-baseline-assumptions-and-scope-for-techno-economic-modelling-of-hydrogen-admixture-into-the-gas-grid/

Can you explain the different blending levels of hydrogen in the natural gas grid discussed in the report, and how do hydrogen separation technologies play a role in protecting hydrogen-sensitive customers?

We can blend hydrogen with natural gas in various proportions, but practical constraints and differences in properties limit the blend. Stakeholder feedback suggested that future blends are unlikely to exceed 20 % at the distribution level and 20 – 30 % at the transmission level.

Hydrogen and natural gas have distinct properties, and as we increase the hydrogen content, the blend diverges from natural gas. There's a practical limit where it's more sensible to transition to pure hydrogen transport.

This is where hydrogen separation technologies come into play. These technologies enable us to extract hydrogen from the blended gas mixture when needed, ensuring that hydrogen-sensitive customers receive the gas they require. By selectively removing hydrogen, we can meet the purity and composition specifications of these customers, providing them with the gas they need for their applications.

In the methodology for network modeling described in the report, could you provide insights into the data sources for transmission network and gas consumption data and their quality?

The European Network of Transmission System Operators for Gas (ENTSOG)[c], established in 2009 under the third EU energy package, plays an important role in Europe's energy market liberalization. ENTSOG is responsible for various tasks, including standardizing network codes, creating a pan-European gas network development plan, enhancing information flow among TSOs[d] and market participants, and developing collaborative tools for network operation.

One such tool is the transparency map, a platform where TSOs share information on network operation, emphasizing market data and actual gas flows. Since its revamp in 2014, the portal also supports hourly measured values. The transparency map offers data access via API calls, which can be automated. To assist our modeling work in HIGGS, we've created a Matlab program for querying necessary data from interconnection points.

How do computer-aided network calculations and software tools contribute to the network modeling process, as mentioned in the report?

Such software allows to efficiently simulate extremely complex systems that cannot be solved with conventional analytical methods and therefore need numerical methods. The quality of the results depends, of course, on the quality of the inputs and the ability to interpret these results correctly.

[c] https://www.entsog.eu/
[d] Transmission System Operator

Regarding conclusions and recommendations could you summarize the four possible gas grid scenarios characterized by H_2 content and the need for separation, as proposed in the report?

1. **0 – 2 vol.-% H_2, no separation:**
   Adding low levels of hydrogen (0 – 2 vol.-%) to the existing gas grid eases the shift to a cleaner energy system. This blend allows gradual adoption, leveraging current infrastructure without extensive modifications.

2. **2 – 30 vol.-% H_2, no separation:**
   Retrofitting the gas infrastructure to handle higher hydrogen levels (2 – 30 vol.-%) allowes continued use of existing appliances. While some upgrades may be needed, this approach minimizes disruptions and supports a gradual shift to hydrogen-based energy.

3. **2 – 30 vol.-% H_2 with separation:**
   Implementing separation technologies in the transmission grid lessens the impact on consumers. The existing infrastructure, retrofitted for higher hydrogen content, can still be used effectively. Using it at key points enables distribution and storage of pure hydrogen, promoting renewable energy integration.

4. **100 vol.-% H_2:**
   Retrofitting the gas grid for 100% hydrogen offers a cost-effective solution. Leveraging the existing extensive grid minimizes construction needs. This transition supports clean energy access, utilizing renewable hydrogen to diversify the energy mix and reduce carbon emissions, aligning with global decarbonization efforts.

D5.4 Techno-economic validation:
Main conclusions and recommendations

https://higgsproject.eu/elementor-2381

What are the technical and economic recommendations based on the findings of the report, especially regarding the compatibility assessment of the existing gas grid infrastructure and necessary retrofits?

The assessment process evaluated the compatibility of the existing gas grid with hydrogen, considering factors like pipeline integrity, valves, compressors, and safety systems. We expected promising results in compatibility studies, particularly for up to 30% hydrogen blends. Once compatibility is assured, we identified retrofitting needs for affected grid sections, which could involve pipeline upgrades, equipment installations, safety enhancements, and system adjustments. Following this, a comprehensive cost-benefit analysis assessed the economic feasibility of retrofitting, considering infrastructure, equipment, safety, and maintenance costs, along with potential benefits like emission reduction and compliance with renewable energy goals. Our analysis in the report D5.3 highlights cost variability in hydrogen transport based on the chosen business case, offering valuable insights for grid retrofitting and blending strategies.

How does the report address hydrogen supply availability, cost, and reliability, and what recommendations are offered to address these economic aspects?

A local perspective must be taken to assess the availability, cost, and reliability of hydrogen supply in the region. The goal must be to be able to offer green hydrogen in a cost-efficient way compared to other generation sources, with full cost accounting. In the end, this means that a price for CO_2 is needed in order to be able to compete for e.g. with grey hydrogen.

The report emphasizes the importance of regulatory environments. Could you explain what favorable regulatory conditions would be needed to support the implementation of the recommendations?

For example, favorable regulatory conditions encompass a range of strategies and policies that can significantly boost the implementation of green hydrogen. Government incentives, such as grants and subsidies, are instrumental in making green hydrogen production economically viable and attracting investments in renewable energy projects. Carbon pricing mechanisms, exemplified by carbon markets and taxes like those in the European Union, incentivize industries to transition to green hydrogen by placing a cost on carbon emissions. Additionally, mandates and targets, like Japan's goal to become a "hydrogen society" or Germany's National Hydrogen Strategy, provide a clear roadmap for the development and integration of green hydrogen into various sectors, including transportation and industry. These regulatory initiatives collectively contribute to the accelerated adoption of green hydrogen as a clean and sustainable energy source worldwide.

In the conclusion of the report, it mentions the need for a holistic European solution. Could you elaborate on the factors that contribute to the need for a European approach in the context of hydrogen injection into gas grids?

In summary, the need for a European approach in the context of hydrogen injection into gas grids arises from the interconnected nature of Europe's gas infrastructure, energy transition goals, cross-border trade, resource distribution, confidence-building measures, infrastructure investment, and collaborative research efforts. A unified strategy ensures that Europe can effectively harness the potential of hydrogen as a clean energy carrier while optimizing its use across diverse member states.

D 5.3 – Intermediate report: key findings on potential and enablers

https://higgsproject.eu/d23-hydrogen-compatibility-in-high-pressure-grids-technical-rcs-barriers-enablers-and-innovations-2

The report suggests the retrofitting of the gas grid for 100% hydrogen as a cost-effective solution. Could you provide insights into the challenges and benefits of such a transition?

Retrofitting the existing gas grid for 100% hydrogen poses hurdles related to material compatibility, safety, high infrastructure costs, and ensuring a stable supply of green hydrogen. Despite these challenges, the transition offers significant advantages, including substantial carbon emissions reduction, enhanced energy security, optimized asset utilization, global cooperation opportunities, cleaner energy sources, technological advancements, and economic benefits like job creation and export potential.

Turning to "D 5.3 – Intermediate report: key findings on potential and enablers," what were the key findings regarding the decrease in large-scale hydrogen separation costs and the cost of transporting hydrogen?

In our study, it was assumed that the membranes would be produced in a large-scale scenario in order to keep the costs low. However, CAPEX do not play such a large role with these membranes. OPEX play a much more important role because such membranes and the separation process itself are very energy-intensive.

How do the findings in "D 5.3" contribute to the overall objectives of the HIGGS project and its potential impact on the European gas grid?

Within HIGGS, D5.3 mainly shows what costs the transport of hydrogen in a converted natural gas grid could cause and puts them in the context of different expansion stages. Furthermore, it shows which solutions could make sense, mainly from an economic point of view, and which are unlikely to ever be realised. The solutions that are economically advantageous are also worth investigating further for their technical feasibility. In D5.4, for example, we concentrated only on either mixtures of ≤30 vol-% hydrogen or then 100 vol-% hydrogen.

3.2 | Baseline, assumptions and scope for techno-economic modelling

During our work, we focused on techno-economic modelling and validation, exploring enablers and interoperability. Our primary goal was clear: to generate operational strategies and illuminate the possibilities for grid operators.

Hydrogen is recognized for its sustainability and integrating it into the high-pressure gas grid describes a crucial step in the decarbonization of the European energy system. Our purpose was to illustrate how this integration could facilitate a more environmentally friendly future.

Furthermore, we conducted an in-depth analysis of the effects of increased hydrogen concentrations within the gas transport value chain, taking into account various stakeholders such as gas producers, transport companies, and gas distribution networks. We utilized a reliable numerical model to unravel the technical and business intricacies, exploring how the grid adapts to varying blending levels and formulating operational strategies for a future enriched with hydrogen.

It's important to note that the introduction of hydrogen into natural gas isn't merely a blending process; it represents a fundamental transformation in the way our transmission systems operate.

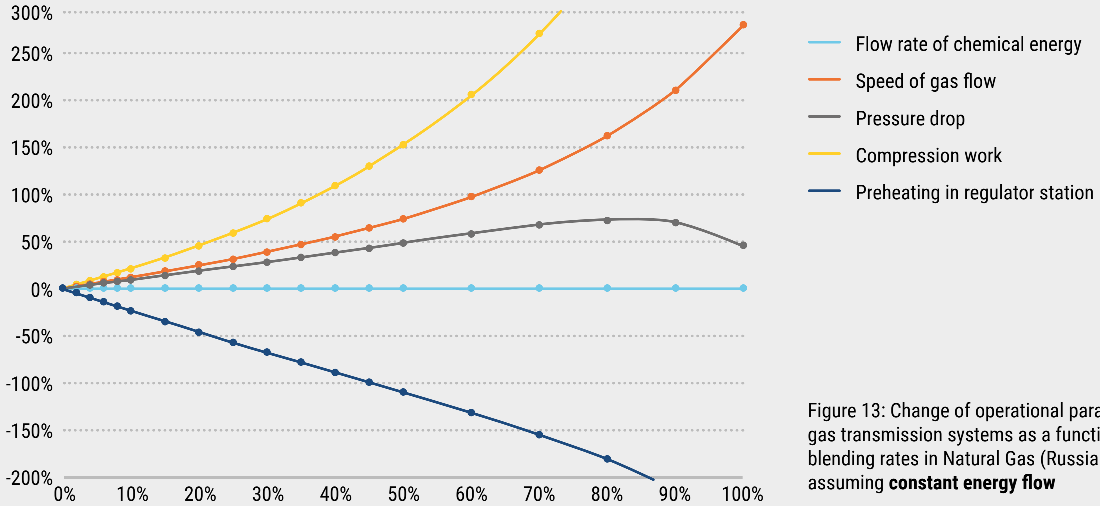


Figure 13: Change of operational parameters of gas transmission systems as a function of H_2 blending rates in Natural Gas (Russian H-Gas) assuming **constant energy flow**

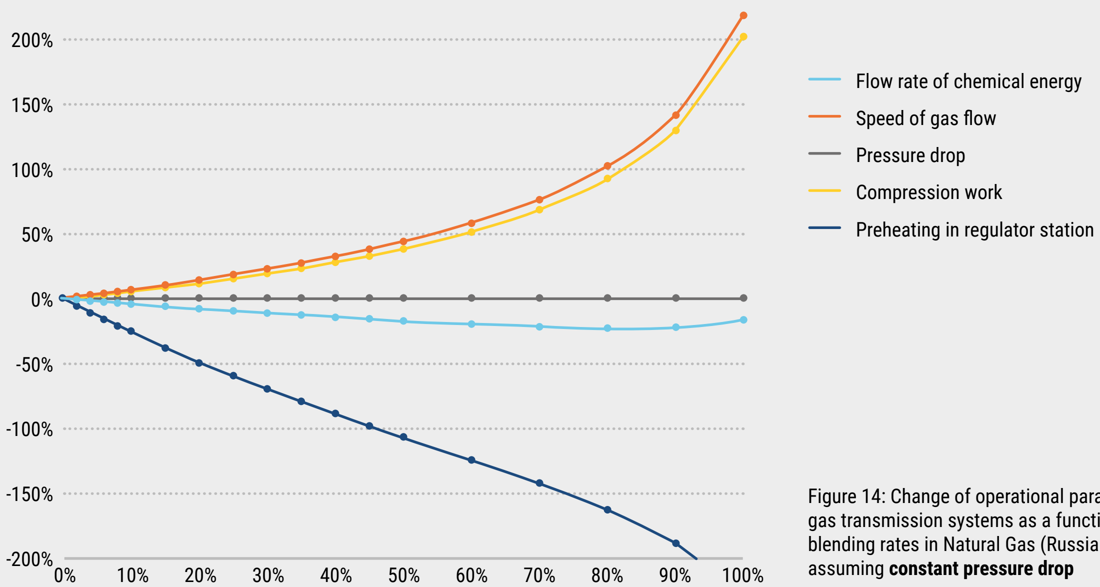


Figure 14: Change of operational parameters of gas transmission systems as a function of H_2 blending rates in Natural Gas (Russian H-Gas) assuming **constant pressure drop**

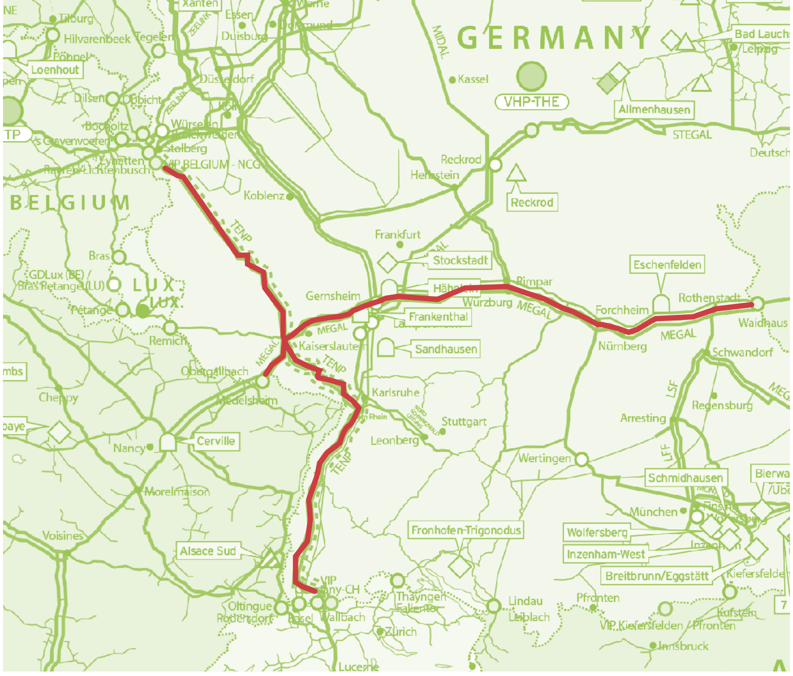


Figure 15: Network modelling of TENP and MEGAL pipeline sections in QGIS

We obtained interesting insights from network development data. Pipeline projects had varying costs, ranging from 1 to 3.5 million euros per kilometer, depending on their size. The costs for reducing stations and city gates could go as high as 20 million euros, depending on the flow rate. Compressor stations, with capacities between 5 and 50 MW, could cost between 25 and 200 million euros.

However, it's important to note that these costs represent only a small portion of the expenses required to adapt the grid for hydrogen blending. To model this complex network, we developed a suitable methodology, which involved gathering crucial data such as pipe dimensions, infrastructure details, and operating conditions. Europe's transmission network resembles a complex neural network with intersecting routes.

One noteworthy intersection was located in southern Germany, where MEGAL (east-west) intersected with TENP (north-south). This served as a model basis for our case studies due to its significance for European energy security and the availability of data for both pipelines.

Information	TENP	MEGAL Nord
Parent Company (-)	OGE (51%) Fluxys (49%)	OGE (51%) GRTgaz (49%)
Operator (-)	TENP GmbH & Co. KG	MEGAL Gmbh & Co. KG
Parallel lines (-)	2	2
Length (km)	2 x 500	459, 449
Diameter (inch)	(36–38, 40)	35, 47
Pressure level (bar)	68	80
Compressor Stations	4	6
Main flow direction	North ⟶ South	East ⟶ West
Capacity (TWh/a)	180.4[1]	246.2[2]
Reverse flow (TWh/a)	52.8	–
Entry/Exit points	4 / 22	5 / 15

Table 1: TENP and MEGAL pipeline information (Trans Europa Naturgas Pipeline GmbH & Co. KG 2017) (FNB Gas 2020) (Global Energy Monitor 2021)

[1] Calculated with GCV of Russian H-Gas of 11.19 kWh/m^3
[2] Calculated with GCV of North sea H-Gas of 11.64 kWh/m^3

3.3 | Description of the model and case studies

Our model involved three crucial steps. We started by applying defined cases to a designated gas network section using the Synergi Gas simulation tool. This step calculated variables like compression efforts, flow velocities, and gas composition. Next, we processed the results using Matlab, extracting quantities needed for technical-economic analysis. Finally, we calculated economic costs based on altered gas properties, factoring in market norms, all with the help of common spreadsheet software.

Modelling not considering future gas separation technologies

We explored blends of 10%, 20%, 30%, 60%, and even 100% hydrogen. High hydrogen proportions may have required substantial retrofitting of the transport network.

Modelling including technology innovations needed

We were particularly focusing on crucial technological innovations related to separation technology. This technology has become essential for specific natural gas consumers to ensure efficient downstream processes. Various separation technologies are available, each with its own set of advantages and disadvantages.

We were also evaluating potential future applications for hydrogen transportation while taking into account separation technologies. Membranes are of particular significance in this context as they have a substantial impact on both capital expenditures (CAPEX) and operating expenditures (OPEX). The specifics of this impact can vary depending on the level of hydrogen injection and local conditions.

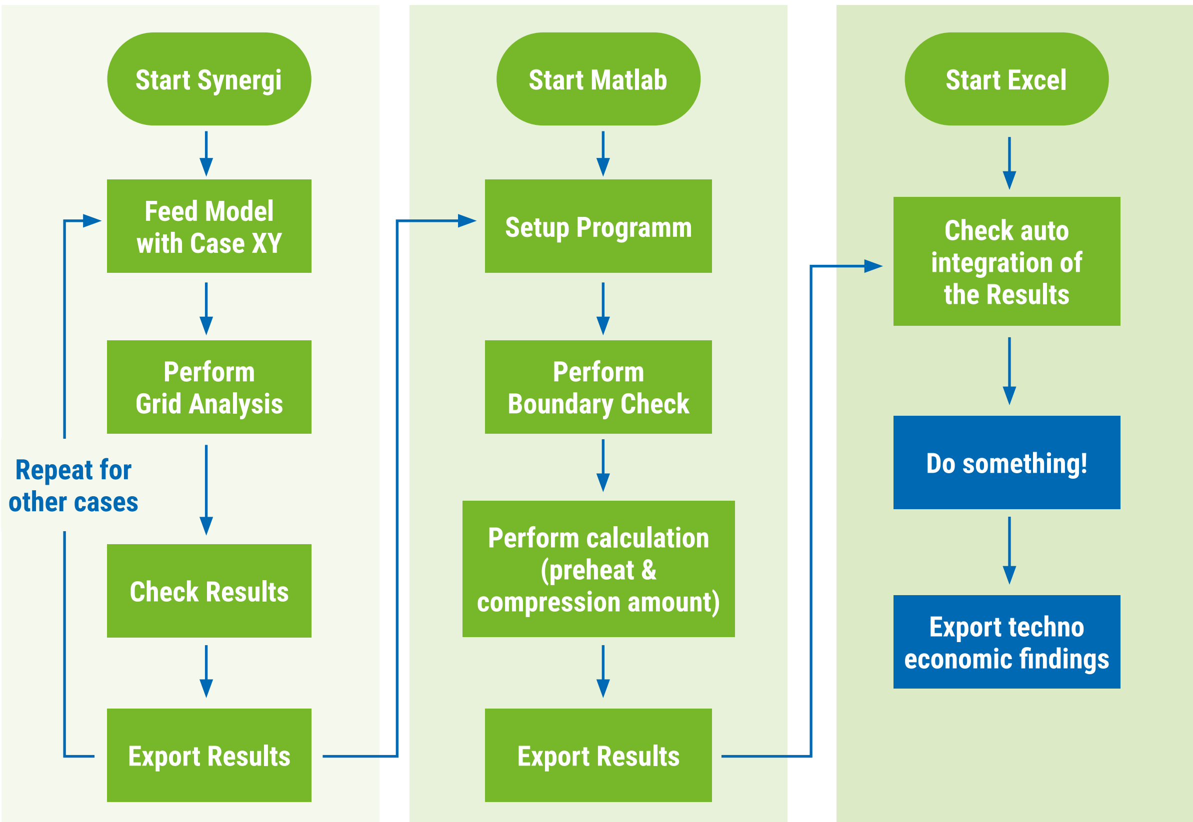


Figure 16: Symbolic workflow from simulation to the economic findings

Pure natural gas

Figure 17 Case 1: Pure natural gas

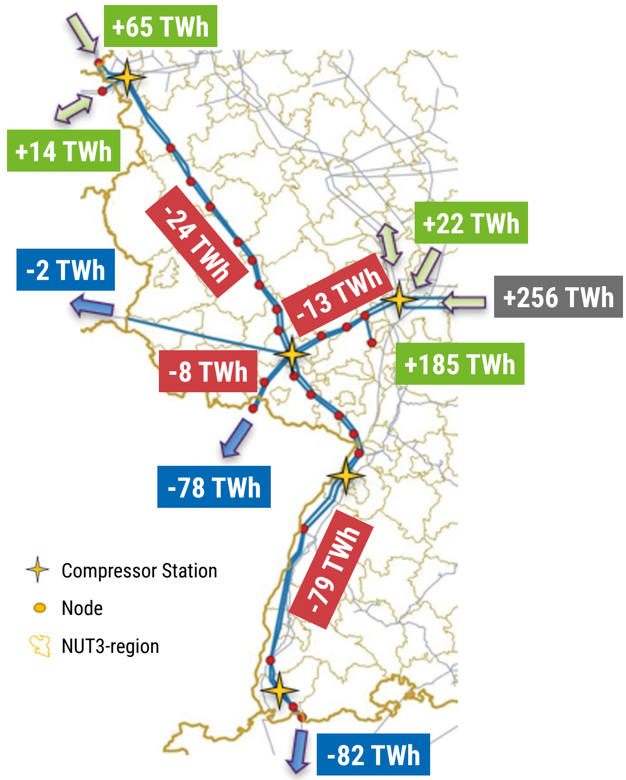
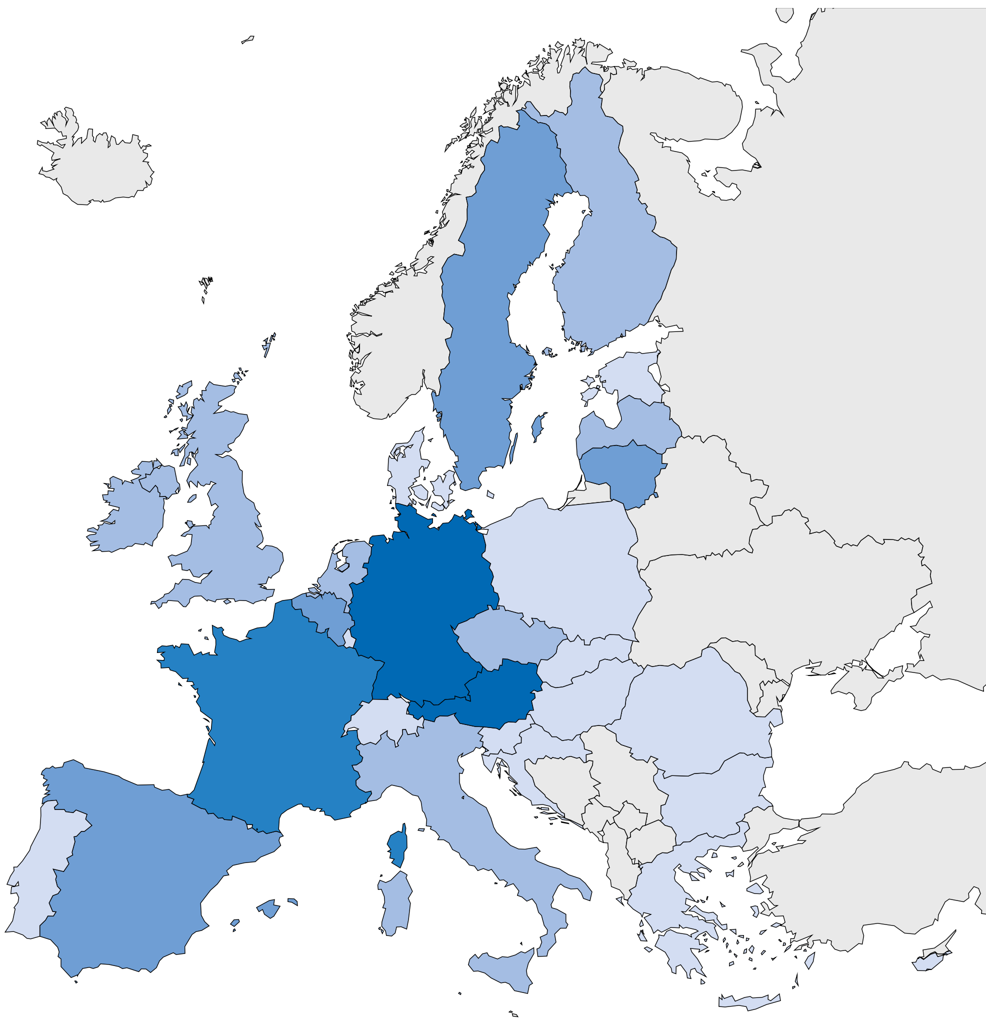


Figure 18: Allowed hydrogen concentration for blending with natural gas in the transmission gas grid of the European member states [HIGGS D2.3]



- 8 < x = 10 Vol-%
- 5 < x = 8 Vol-%
- 1 < x = 5 Vol-%
- 0 < x = 1 Vol-%
- 0 Vol-%

3.4 | Key findings on hydrogen admixing potential and enablers

The costs of hydrogen transport, as computed in our project, aligned with those suggested by other studies like the European Hydrogen Backbone. The figures ranged from approximately 3 – 5 €/MWh/1000 km without membranes, showing that high-pressure pipelines were the most cost-effective option.

When membranes at all city gates are added, the costs increased significantly, landing at around 11 – 47 €/MWh/1,000 km. This brought alternatives like compressed gas or LOHC transportation into the spotlight, particularly in summer.

With a targeted membrane use, the transport of hydrogen through a retrofitted natural gas grid became an attractive proposition, with costs ranging from approximately 7 – 11 €/MWh/1,000 km. But local conditions, demand, and hydrogen concentration allowances are key determinants here and need further investigation.

As for converting the entire European gas grid, it is a complex puzzle with varying regional factors. A local analysis is essential to provide a well-founded perspective.

Case 2.1: premixed gases at inlet of modal

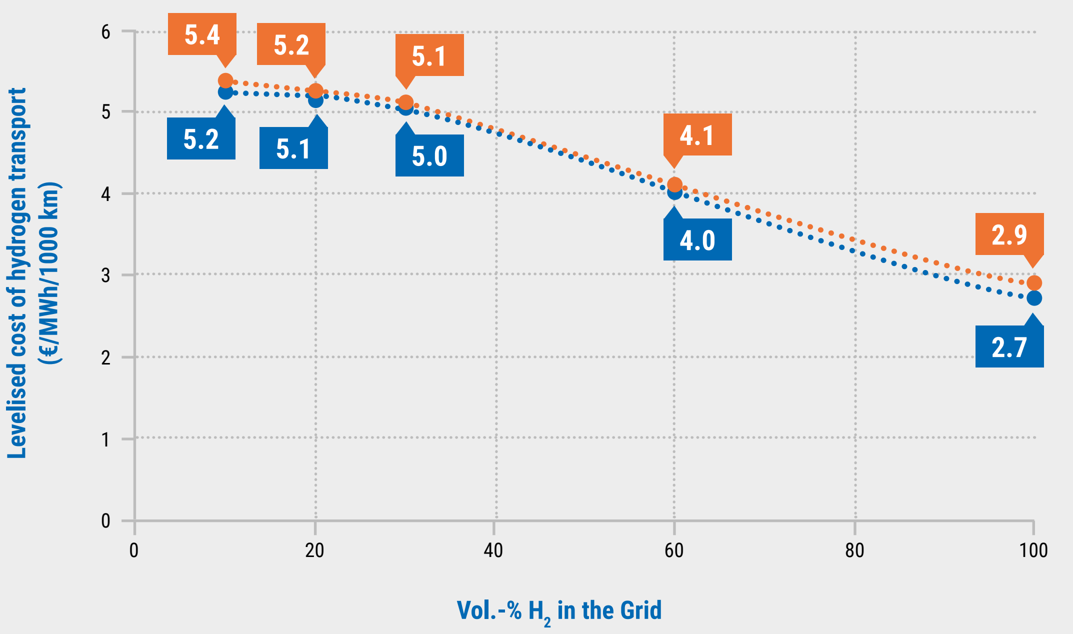


Figure 19: Levelised costs for hydrogen transport via retrofitted pipeline transmission system at different admixture levels

Case 2.2: Moderate use of hydrogen

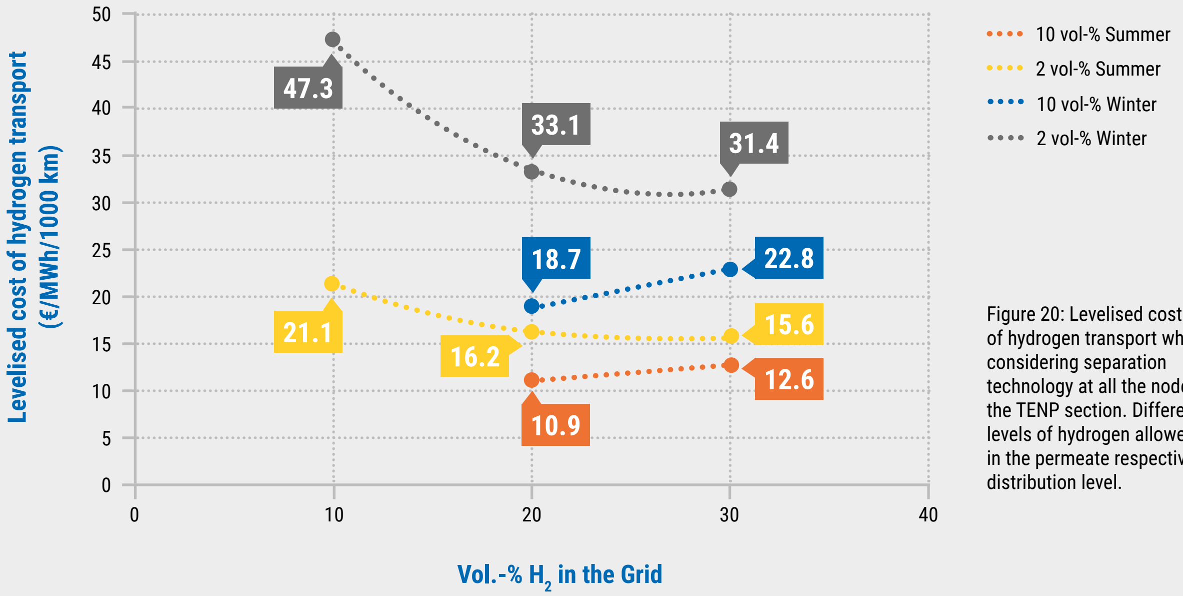


Figure 20: Levelised costs of hydrogen transport when considering separation technology at all the nodes of the TENP section. Different levels of hydrogen allowed in the permeate respectively distribution level.

3.5 | Main conclusions and recommendations

From a business and operational perspective, the future gas grid scenarios present opportunities and risks. Legal barriers to hydrogen transport need reduction across Europe, and supply and demand must expand. Scaling green hydrogen production and addressing renewable energy storage is essential.

From a technical standpoint, we emphasised compatibility assessment, system retrofitting, optimal blending ratios, and the strategic use of separation technology. A hydrogen-dedicated grid may be the long-term goal.

Economically, conducting comprehensive cost-benefit analyses, ensuring hydrogen supply, advocating for favorable regulations, engaging stakeholders, and planning for the short- and mid-term viability are critical.

Ultimately, transforming the European gas infrastructure to hydrogen is a multifaceted challenge that lacks a universally applicable solution. Collaboration between regions are key to building a resilient gas grid that can meet Europe's energy needs in a flexible and sustainable way.

Our work has shown that transporting hydrogen through a retrofitted gas grid is not only economically competitive but a necessity to achieve emissions targets. Our journey continues, and the path to a sustainable energy future is clearer than ever.

4 Pathway Towards Integrating H_2 in EU Gas Networks

The main objective of the work package on the pathway towards integrating hydrogen in European gas networks was to compile the main findings and assessments during the project, in the form of a pathway for the enabling of higher concentrations of hydrogen in the natural gas transmission grid. The pathway builds on work packages that were conducted in an earlier phase of the project. The specific objectives were:

- Documenting the potential of hydrogen injection as enabler towards EU policies on decarbonization.
- Establishing a list of potential issues, barriers and facilitators for cross-border and interoperability in the gas grids.
- Preparing a document with summary of the findings and proposals for admixture and injection facilities, towards establishing an optimal design.
- Updating the proposals on regulations, codes and standards for further development and higher acceptance of hydrogen in the gas grid, based on HIGGS results.

4.1 | Michael, did you face challenges in carrying out the proposed work?

We faced challenges from the second project year on and they are still here to be tackled. In spring 2019, the time we wrote the proposal for HIGGS, one thing was clear – hydrogen is here and it is time to bring the results from the Fuel Cells and Hydrogen Joint Undertaking project to market. This was requested by Maroš Šefčovič, at this time European Commissioner for Energy (now Executive Vice President of the European Commission for the European Green Deal), during the FCH JU's stake holder forum, which took place on November 16, 2018. This was taken up in the proposal, having in mind, that hydrogen penetration into the European market will take place as hydrogen admixing into the European gas transmission grids. The hydrogen uptake took the plans of the North Sea countries to use natural gas platforms, connected to closely to them erected wind farms, as platform for water electrolysis, injecting the produced hydrogen into the existing pipeline systems, transporting hydrogen from offshore to onshore, where it would have been distributed through the existing natural gas grid (transmission as well as distribution grids) into account.

Dr. Michael Walter
Manager R&D Innovation Programme Hydrogen,
DVGW e.V.

One year after, in 2019, during the negotiation phase of the HIGGS project, at the same event but on November 21st., Frans Timmermans, at this time First Vice President of the European Commission at the time, stated with other words, that the hydrogen momentum is here. In my own word, being witness of both speeches, Frans Timmermans meant that there is no time to discuss anymore, it is time for doing (short "Doe het" in Dutch). This led to the initiative of the European Hydrogen Backbone, in which major transport system operators. Another effect was, that, on demand of the European Commission and European Council, all European Member states should prepare national hydrogen strategies. In 2020, the year in which HIGGS started, everything went smooth in carrying out the proposed work. However, from 2021 on the challenges came into the game. On the hydrogen admixture into natural gas transmission grids, it became uncertain if this will happen. The discussion on the European Gas Package Regulation led to the fact, that cross-border transport of gas will not be permitted with hydrogen concentrations higher than 5 volume-%, unless bilaterally agreed. As the Gas Package is presently in the trialogue, HIGGS has to monitor the process precisely, not to delivery outdated data. Similar happened to tasks, in which questions towards standards where to be addressed. Thus, HIGGS had to rethink its proposed work several time throughout the course of the project.

What the single questions were and how HIGGS has dealt with the challenges was elaborated by the following project partners: Dr. Stefan Gehrmann and Hiltrud Schülken, both DVGW, Dra. Lola Storch de Gracia, Alberto Cerezo Alarcón and Cristina Rodriguez Vilariño, all three REDEXIS and Dr. Jávier Sanchez Laínez, FHa.

4.2 | Stefan, you are tackling the cross-border issues as well as the gas market related management and strategic topics. What was the main finding till now you achieved?

The project has had to adapt several times due to the dynamic environment you find yourself in when dealing with hydrogen. At the beginning of the project, it could be assumed that the blending of hydrogen into the transmission network would play an important strategic role, in order to get hydrogen in large quantities from regions with high production and import potential to regions with high demand. However, the discussions on a maximum blending limit at cross-border interconnection points in the "Hydrogen and Decarbonized Gas Market Package" and the results of a survey among European Transmission System Operators in the course of the HIGGS project show that a separation between pure hydrogen networks and natural gas networks with limited blending is more likely.

Does this mean that hydrogen blending will play little or no role?

No. We do expect hydrogen to be blended into the natural gas network. In accordance with the regulations of the Gas Package in the transmission network up to a certain cap for cross-border trade, which is still under discussion. This is important in order to maintain a certain degree of flexibility, even though this cap will most likely be 5 percent by volume or less. In addition, the gas package explicitly allows for higher blending rates in national networks and, in the case of bilateral or multilateral agreements, also for cross-border trade. This may play a role in certain regions if the requirements can be met and there are strategic or infrastructural advantages. In addition, it has to be stressed that there will be significantly higher blending rates in the distribution networks during the transformation process, but also in the final state with biomethane. The European Distribution System Operators and their customers are currently setting the course for making the distribution networks carbon-neutral in this way.

Dr. Stefan Gehrman
Technical Manager Energy Research
DVGW e.V.

4.3 | Hiltrud, the HIGGS work has a task dealing with the standardization of hydrogen injection into the gas transmission grid. What is the actual status on this?

Currently, the CEN Technical Committee for gas infrastructure (CEN/TC 234) is elaborating a series of standards with requirements for hydrogen injection stations (EN 17928 parts 1 and 3). The documents passed public enquiry stage successfully and will be subject to final voting in Q1-2024. Publication is then awaited in Q3-2024. However, the general technical hydrogen suitability of the system and hydrogen quality specifications are also key to enable the safe and reliable injection of hydrogen into the gas grid. A CEN Technical Specification on hydrogen quality in rededicated gas systems (CEN TS 17977) is available, now, and a standard on hydrogen quality for the future hydrogen grid will follow with the support of a standardisation request on behalf of the European Commission to CEN and CENELEC.

For the readiness of the grid, it is particularly important to thoroughly consider the potential impacts of hydrogen on materials such as embrittlement of steel, permeation through materials, suitability of elastomers and sealing materials, on safety aspects such as purging/venting, gas tightness, leakage, detection as well as on the technical system such as compression, metering and much more. Thus, the relevant standards are currently subject to investigation on revision needs to make them hydrogen-ready; some are already in revision where the relevant hydrogen aspects are already identified and might need to be revised at later moments when additional findings are available. Several additional standards and standardisation deliverables are also already identified and partly started, as the standard on hydrogen injection stations (see above), the standards for compressor stations (EN 12583) or for the conversion of high-pressure pipelines from natural gas to hydrogen (just started).

The HIGGS deliverable D2.3 describes the European standardisation in the context of the European legal framework and EC strategies. It gives non-exhaustive lists of relevant CEN, CENELEC and ISO Technical Committees as well as of relevant standards. The updates for new developments in the standardisation for transmission gas grids, have and will be conducted. Standardisation necessities have also been deducted, especially regarding the results of the material testing performed in the project.

D2.3 – Hydrogen compatibility in high-pressure grids: technical, RCS barriers, enablers, and innovations

https://higgsproject.eu/d23-hydrogen-compatibility-in-high-pressure-grids-technical-rcs-barriers-enablers-and-innovations/

Hiltrud Schülken
Department Manager International Relations Gas
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4.4 | Javier, what is the potential of the hydrogen injection in Europe and is it in alignment with the EU policies?

According to our work around the considerations on H2 injection potential to reach European decarbonization goals, the potential seems to be significant, as various countries are either planning to import or export hydrogen in the coming years. The analysis we have performed suggests that different European countries have varying levels of capacity for hydrogen import or export, with some countries projected to become significant hydrogen exporters by 2030 and 2045/50. The most relevant hydrogen-demanding countries would be Switzerland and Germany, followed by Belgium, Czech Republic, Hungary, or France. The major exporting counties would be Finland and Spain, followed by the Netherlands, UK, Portugal, Norway, and Ukraine. It can be seen how peripheral countries in Europe are expected to "feed" hydrogen to the central part of the continent.

In terms of alignment with EU policies, the EU has been actively promoting the use of hydrogen as a clean energy source to achieve its climate goals. The EU has set ambitious targets for reducing greenhouse gas emissions and has included hydrogen as a key component of its long-term energy strategy. The EU's Hydrogen Strategy, published in 2020, aims to facilitate the development of a hydrogen market and infrastructure across Europe. Additionally, the EU Gas Directive and TEN-E regulation have laid out a framework for injecting hydrogen into gas grids, thus supporting the integration of hydrogen into the existing energy infrastructure. All these policies aim to foster a hydrogen economy for sustainable energy transition, but can face challenges such as high production costs, limited infrastructure, and energy-intensive production processes, which may hinder its widespread adoption. Additionally, their reliance on renewable energy sources poses challenges in terms of intermittency and scalability.

However, it is crucial to note that the regulatory framework may evolve, and ongoing negotiations might result in changes to the policies governing hydrogen integration. The regulatory framework for hydrogen injection is expected to undergo several key developments, including an emphasis on safety issues and material compatibility, stricter emission and the introduction of more incentives and subsidies to encourage the adoption of hydrogen technologies. Thus, it is essential for stakeholders to remain updated with the latest developments in EU policies and regulations related to hydrogen.

The potential of hydrogen injection in Europe is significant and is often considered a crucial component of the region's future energy strategy. Hydrogen has the potential of becoming a potential alternative to electrification. While EU policies largely support the shift from natural gas to hydrogen, their effectiveness may not be sufficient. Calls for stronger private sector incentives, clearer infrastructure development plans, and potential considerations for hydrogen grid operators are necessary for the full development of hydrogen grids. Continuous policy review and adaptation are therefore crucial for a successful integration.

Dr. Javier Sánchez Laínez
Coordinator of hydrogen conditioning and transport - R&D
Fundación Hidrógeno Aragón

4.5 | Lola, Redexis is a gas system operator in Spain. How do you see the chances and potentials of hydrogen in the Spanish and European grid and do you see obstacles herein?

The Spanish and European gas grid will play a crucial role in the transition to renewable energies and the European energy future. This perspective considers various aspects. Firstly, it aligns with European sustainability policies, utilizing existing, fully operational infrastructure. These infrastructures were partially constructed based on remuneration terms, thus funded collectively. They are also highly compatible with hydrogen, whether in blending with natural gas or utilizing 100% hydrogen. The network requires minimal adaptations for low mixing percentages (≤10%). Moreover, these infrastructures extend to end consumers, allowing direct access to hydrogen.

Secondly, the injection of hydrogen into the network can occur through various methods, primarily involving the blending of natural gas and hydrogen (up to 30%) or the dedicated use of natural gas infrastructure with 100% hydrogen.

Considering the existing networks for natural gas, the potential for hydrogen in Spanish and European grids is remarkable. Europe's commitment to sustainability necessitates enabling the means to facilitate transmission and distribution system operators to offer their networks for this new energy vector. Injecting hydrogen into natural gas networks is not only economically viable but also socially and environmentally responsible, reducing the impact on natural resources and expanding access to this energy source for all users. This approach aligns with the 2030 Agenda's goals and supports the transition challenge faced by current natural gas operators. Regarding the challenges and how the HIGGS project tackled them, several key points stand out:

- Regulatory and normative gaps: The HIGGS project assessed European legislation and regulations, identifying knowledge gaps and proposing actions to address them. This counts e.g. for hydrogen blending, as it is not clear yet what the provisions in the European standards need to cover, due to the lack of strategic commitments[1].
- Technical and technological gaps: The project identified the materials and components within European natural gas transportation networks and analysed their performance when dealing with gas and hydrogen mixtures, as well as 100% hydrogen. The evaluation showed that these components are compatible for potential use in hydrogen networks.
- The HIGGS Project tested various membrane technologies for separating gas and hydrogen mixtures. These technologies could serve as means to protect users that are not compatible with a certain hydrogen rate.

Dra. Lola Storch de Gracia
Head of Innovation
Redexis

[1] https://higgsproject.eu/d23-hydrogen-compatibility-in-high-pressure-grids-technical-rcs-barriers-enablers-and-innovations/

4.6 | Alberto, what was your task within the work package on the pathway towards hydrogen integration and could you give us information on the results?

REDEXIS is involved in all asks of the work package, but our primary contribution centers on the task that addresses gas market and operation considerations. In this task, we gathered information on the conditions governing the operation, maintenance, and market of natural gas transmission in Europe. We examined how TSOs and transmission infrastructure management bodies operate networks and analysed how these conditions were affected by hydrogen injection, which will require the operation of networks with a gas different from the original. This analysis offers a new perspective on the impact of hydrogen injection, identifies key factors for consideration in new operating conditions, and provides recommendations to authorities and stakeholders for the development of codes that enhance interoperability in the integrated gas market

Why is the HIGGS Project important for Redexis?

Redexis is a natural gas transmission and distribution operator involved in the energy transition, actively supporting the development of renewable gases, such as green hydrogen and their integration into our gas networks. We faced barriers such as the absence of a clear legal and regulatory framework and limited knowledge of the effects of hydrogen injection on our infrastructure. The HIGGS Project directly addressed these issues, offering well-founded proposals for developing new regulations for hydrogen injection and practical insights into material behaviour in transmission networks. These contributions are essential for evaluating the suitability of our infrastructure for decarbonization and building trust among operators, authorities, users, and society.

What practical results has Redexis obtained from HIGGS so far?

In parallel with the HIGGS Project, Redexis is developing the first pipeline that is dedicated to transport 100% hydrogen (hydroduct) and hydrogen injection system in the Spanish natural gas transmission grid as part of the GREEN HYSLAND project[2]. The materials study conducted within HIGGS has helped us select suitable steels for constructing the GREEN HYSLAND hydroduct and mixing system. The absence of specific regulations has caused delays, but we received final approval for the infrastructure in September 2023. Additionally, we've gained knowledge about the compatibility of steels and components in hydrogen transmission grids, enabling a preliminary analysis of hydrogen's compatibility with our networks and the necessary adaptations for injecting high quantities of hydrogen in blending and using 100% hydrogen.

Alberto Cerezo Alarcón
Deputy Director of Innovation
Redexis

2 https://greenhysland.eu/ Clean Hydrogen Partnership, Grant Agreement Nº 101007201

4.7 | Cristina, as a young engineer, what is your perspective on hydrogen admixing?

Since the Second Industrial Revolution, energy demand, which has continuously increased over time, is primarily divided between what is covered by electricity and what is directly fueled by fossil fuels. We are currently at a point where energy demand is more than three times higher than it was 50 years ago, with the energy sector being one of the most polluting sectors. Therefore, to reduce greenhouse gas emissions, it is essential for the sector to undergo a significant transformation so that, in the long term, it can be considered entirely renewable.

One of the transformations that the energy sector needs to undertake is specifically in the gas sector. Contrary to what many may believe, this transformation does not entail, nor should it entail, a complete overhaul of the existing infrastructure or its operational procedures, but rather a shift in the type of gas it transports. Instead of supplying natural gas, we should transition to supplying renewable gases such as biomethane, biogas, syngas, or renewable hydrogen. Among various renewable gases, hydrogen has been positioned as a key solution for decarbonizing the major polluting sectors, surpassing other renewable gases like biomethane. Not only does it enable the treatment of waste that went untreated in the past, but it also has the advantage of closely resembling natural gas, making it highly compatible with the current grid.

It's important to note that Europe regulates an infrastructure of over 200,000 kilometers of transmission grids and more than 2,000,000 kilometers of natural gas distribution grids for the transportation and delivery of natural gas. Consequently, its long-term use is not a viable option. Rather than constructing entirely new infrastructure for hydrogen, it makes great sense to adapt the existing natural gas grid for hydrogen injection, thereby reducing the economic impact of building new infrastructure and increasing the societal impact by offering customers a renewable gas. We should consider the cost-effectiveness of repurposing existing natural gas grids for hydrogen, as compared to constructing new grids. There are statistics from organizations like MARCOGAZ that highlight these cost differences[3]. An open approach is crucial, where both repurposing and admixing are seen as viable options, especially in research and innovation efforts.

Hence, the future of the energy sector, specifically the gas sector, should revolve around the utilization of current infrastructures for the transportation and delivery of renewable gas. This infrastructure would only need to make the necessary adjustments to accommodate the transportation of renewable gas.

Cristina Rodriguez Vilariño
Operational Innovation Engineer
Redexis

[3] https://www.marcogaz.org/publications/methodology-document-of-h2-transformation-study/

4.8 | The potential of H_2 injection in European grids

In the first part, the report (D6.1 Considerations on H_2 injection potential to reach EU decarbonisation goals) details the process of gathering information from 59 European Transmission System Operators (TSOs) to compile an inventory of pipelines and transport facilities. Key parameters such as diameter, Maximum Operating Pressure (MOP), and installation periods were considered. The results show that France, Germany, Italy, and Ukraine have the longest grids, while 73% of European pipelines lack information about installation periods and 83% lack MOP data. The data is grouped into five geographic clusters based on diameter and MOP, showing that pipes with diameters over 40 inches are prevalent, and MOP mostly falls within the 70 – 85 bar range.

In the second part, a survey was shared with TSOs and gas associations in Europe to gather specific information about their grids, including pipe and welding materials, coating materials, odorization systems, and gas quality control systems. Data from approximately 73,000 km of the European transmission gas grid was collected. It also discusses the maximum admissible hydrogen concentration in transport gas grids, updating the information provided in a previous report from 2021. Additionally, the report analyzes the potential for hydrogen injection in European transport grids and its alignment with EU policies. Three scenarios are considered:

- baseline scenario (2020 – 23)
- mid-term scenario (2030)
- long-term scenario (2045/50)

The mid-term scenario predicts hydrogen transit across Europe by 2030, taking into account total gas demand, hydrogen production, and demand in different countries. In the minimum demand scenario, Switzerland and Germany have the highest hydrogen import needs, while Finland and Spain are major exporters. In the maximum demand scenario, Germany and the UK become the highest hydrogen importers, while Ukraine is the top exporter. The long-term scenario predicts hydrogen transit by 2045/50, with Belgium, France, and Poland having the highest import needs in the minimum demand scenario. In the maximum demand scenario, Germany and the UK remain top importers, while Ukraine becomes the top exporter.

Overall, the document provides a comprehensive overview of the state of European natural gas grids and the potential for hydrogen injection to meet decarbonization goals.

D6.1 Considerations on H_2 injection potential to reach EU decarbonisation goals
https://higgsproject.eu/d6-1-review-of-the-potential-of-h2-injection-in-european-grids/

The final results on standardization, regulation, and certification (D6.2 Report on main interoperability and cross border issues) as well as the pathway for H_2 injection in the EU gas grids (D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks) are currently undergoing finalisation (as of November 2023). They will be published and available under the following link in January 2024.

D6.2 Report on main interoperability and cross border issues
https://higgsproject.eu/d6-2-recommendations-for-future-standardization-regulation-and-certification/

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks
https://higgsproject.eu/d6-3-pathway-and-recommendations-summary-to-enable-wider-injection-of-h2-in-eu-gas-networks/

5 Outlook

5.1 | Summary of the Project's Achievements and Contributions

The HIGGS project, which stands for Hydrogen in Gas Grids, represents a research initiative with the ambition to investigate the hydrogen admixture possibilities to the European transportation grid up to the point of 100% admixture – re-purposing – of the grid. As one of its primary objectives, HIGGS has created an extensive inventory of the materials in current pipelines and transport facilities. The evaluation thereof has identified parts of the grid that would be most susceptible to operational issues when integrating hydrogen, to be subject to further investigation during the project. The project has also investigated the financial aspects and the potential impact on gas consumers.

The project has undertaken an in-depth review of the existing regulatory standards and codes relevant to the seamless integration of hydrogen in the gas grid. This review encompassed an analysis of European sector initiatives, national frameworks within the European Union member states, and certification and testing programs. The work on this in the project has supported the development of reliable approval procedures for pilot projects and gas transmission grid expansion, thereby helping to pave the way for future integration based on standardized protocols. HIGGS has established a state-of-the-art experimental facility customized to meet the project's specific requirements and evolving industry standards. Equipped to accommodate the dynamic demands of the project, this facility enables the comprehensive study of the impact of hydrogen on various materials, equipment, and components of the grid. Flexibility is a core feature, allowing for the simulation of multiple hydrogen-methane blends at high pressures, reaching up to 80 bar. Furthermore, the facility enables the testing of 100% pure hydrogen injections, providing a detailed understanding of its effects.

An extensive testing program during the project has investigated a range of critical components within the grid infrastructure in regard to their tolerance of different concentrations of hydrogen in natural gas up to 100% hydrogen and 80 bar pressure. This also included some functionality aspects such as evaluating the tightness of different types of valves. Major focus was put on the evaluation of the pipe steels used in the high pressure grid. But the tests also examined the resilience of further key components such as pressure regulators, filters, and flowmeters. Stringent testing standards compliant with industry norms have guided these evaluations, with a focus on potential embrittlement risks associated with carbon steels ranging from API 5L qualities of X42 to X70.Commencing with a blend of 20 mol% hydrogen, the concentration was incrementally increased to reach 100% pure hydrogen. Additionally, trace impurities of H_2S and CO_2 were introduced during the testing, ensuring a comprehensive understanding of the potential challenges and interactions within the grid infrastructure.

In addition to materials testing, the project conducted technoeconomic assessments to evaluate the financial and technical aspects of repurposing the gas grid for hydrogen integration. These assessments have indicated that repurposing the gas grid for hydrogen is both technically feasible and economically reasonable, providing a strong rationale for further exploration of hydrogen integration within the gas grid.

It is noteworthy that, while transmission system operators (TSOs) currently favor a full re-purposing to 100% hydrogen in parallel with only very low levels of hydrogen admixture at the transport level (max. up to 5%) in other sections of the grid, the role of distribution system operators (DSOs) in the context of hydrogen integration, particularly at the European level, remains a subject of interest in concern to higher rates of hydrogen admixing. As hydrogen gains prominence as a clean energy carrier, the actions and perspectives of DSOs are of increasing significance, and future developments will shed light on their role in the transition to a hydrogen-integrated gas grid.

In summary, the HIGGS project has contributed to the compatibility of gas grid materials with hydrogen and the technoeconomic feasibility of hydrogen integration. These results have laid the groundwork for a potential shift toward a more sustainable and hydrogen-enriched energy landscape in Europe.

5.2 | Potential of Hydrogen for Grid Decarbonization

The integration of hydrogen into gas grids holds significant potential for contributing to the decarbonization of various sectors and industries. Replacing natural gas with renewable hydrogen can serve as a clean and emission-free energy carrier, effectively reducing carbon emissions associated with traditional energy sources.

This integration enables a transition to a cleaner energy system, allowing for the use of hydrogen in heating, industrial processes, and power generation. This, in turn, plays an essential role in achieving climate targets and reducing the overall carbon footprint of various sectors. Additionally, hydrogen can serve as a means of energy storage, enabling the storage of excess renewable energy generated during peak production periods and ensuring grid stability and flexibility to accommodate fluctuating energy supply and demand.

Integrating hydrogen into gas grids diversifies the energy mix, reducing reliance on fossil fuels and promoting the utilization of renewable and low-carbon energy sources. This diversification enhances energy security, resilience, and sustainability, ensuring a more stable and sustainable energy supply for the future.

5.3 | Challenges & Opportunities – need for Research & Development

During the duration of the HIGGS project, the topic of the integration of hydrogen into the high-pressure natural gas grid has advanced substantially. Both in regard to the work done within the project and also due to parallel activities and results from projects outside of HIGGS. Prominent gas grid operator initiatives moved forward such as; the European Hydrogen Backbone of the TSOs and Ready4H2 of the DSOs. But also national driven projects pushed the boundaries here.

Topics that were not addressed within the HIGGS project in regard to materials were the development of technologies to minimize hydrogen's impact on existing networks, the identification of new materials for hydrogen transport and distribution, and the adaptation of leak detection tools.

While most investigated steels have proven resistant to hydrogen, research beyond the scope of the project would be necessary to define them as “hydrogen-ready”. Challenges such as long-term embrittlement, permeation, and corrosion tests, especially under fatigue conditions, amongst others. Predictive modelling also emerges as a key component of future research, that was not part of HIGGS. Developing models that can predict the long-term behavior of materials under the influence of hydrogen is essential. From the HIGGS project scope point of view the next logical step would also be to standardize test procedures to evaluate how different materials respond to hydrogen-rich environments. These tests should encompass a range of pressures and temperatures to provide a comprehensive understanding of material behavior under various conditions. The test platform developed in HIGGS could be useful for these types of tests and would be useful for further going experiments.

In parallel to the project, national research and development have advanced. "SyWeSt H2", for example, have confirmed the experimental results within HIGGS and comes to the conclusion that the German natural gas transport pipes are hydrogen ready from a materials point of view. These results are transferable to large portions of the total European grid since the same materials are often used. Furthermore, one of the partners in HIGGS, DVGW, offers substantial support to grid operators on all pressure levels to qualify their grids as hydrogen ready, both with guidelines and with an extensive database, where grid operators can match their used materials and components with the state-of-knowledge in regard to hydrogen readiness (VerifHy). HIGGS-project investigated the high pressure grid, but it is important to have the complete value chain in mind. The aggregated distribution grid can be presumed to be up to ten times longer than the transport grid and connects 99% of industrial and commercial end-users. According to the Ready4H2 initiative the materials used in gas distribution are, to a large extent, with more than 1,000,000 km also hydrogen ready.

In order to match the speed of action required by the climate targets in the European Green Deal, the topic of hydrogen in gas grids must reach maturity within the next decade. Emphasis in research and development should be put on challenges in regard to the safe operation of hydrogen grids and demonstration actions.

Efforts should involve decentralized hydrogen injection into the distribution grids, ensuring efficient gas distribution and quality maintenance. Demonstrating the reliability and security of gas supply and gas applications in the energy systems relying on large shares of fluctuating energy by wind and solar is another essential aspect, where large scale hydrogen transport across Europe will have an important role to play. Furthermore, retrofitting industrial site grids to accommodate hydrogen, as well as the gas infrastructure connecting the European mainland to renewable and low-carbon hydrogen are portions of the existing natural gas grids that yet have seen little attention in European research and development programs. In regard to blending of hydrogen, the interoperability with Biomethane in distribution grids is an essential aspect and the development of operation strategies and technologies where sections of the grid have different gases and gas qualities within the same region are also needed.

In summary, the findings of the HIGGS project underline the potential of hydrogen in the decarbonization of the European energy landscape. The successful integration of hydrogen into gas grids offers a promising path towards achieving ambitious climate targets, facilitating a transition to cleaner energy systems, and reducing carbon footprints across various sectors. By leveraging hydrogen as a clean energy carrier, Europe could establish a more sustainable, resilient, and diverse energy mix. However, continuous research and development in key areas are crucial. These activities need to be intensified and supported in demonstration and flagship projects.

HIGGS

Hydrogen in Gas Grids

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