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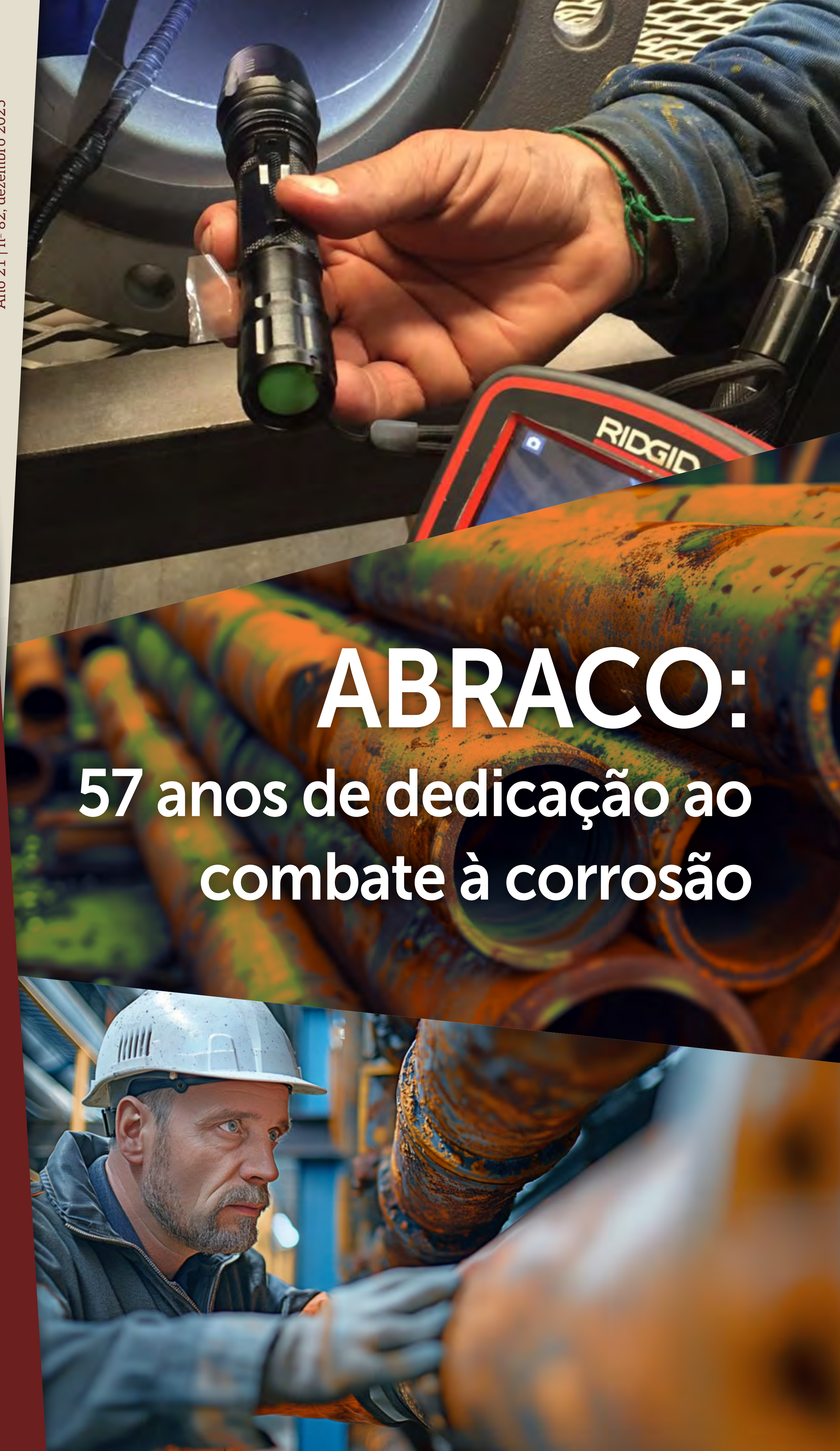

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STUDY OF HYDROGEN TRANSPORTATION THROUGH EXISTING NATURAL GAS PIPELINES

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1. Introduction

In Brazil, the transportation of natural gas through pipelines is already a well-established activity. The need to transport hydrogen gas, in mixtures with natural gas, places us face to face with some issues that need to be thoroughly evaluated. The big question is can we use existing pipelines to transport hydrogen and gas mixtures.

The global imperative to transition toward sustainable energy vectors necessitates the comprehensive integration of hydrogen (H2) into existing energy infrastructure. As a clean-burning fuel and a versatile energy carrier, hydrogen presents a significant opportunity for decarbonizing high-demand industrial sectors. A critical bottleneck in this transition is the establishment of safe, efficient, and economically viable long-distance transportation methods. Utilizing existing natural gas pipeline infrastructure for H2 blending and transport is broadly acknowledged as the most capital-efficient pathway.

In this context, was organized an event, in a workshop format, that originated this paper also featured the participation of members of YPP-BR (Young Pipeline Professionals Brazil), who have presented technical summaries of a group of 17 selected articles. The event was held at Technological Center for Pipeline and Terminal (CTDUT) facilities, as part of the research and development roadmap of Hydrogen transportation by pipelines.

2. Technical Topics

From the selected papers we prioritized five technical topics highlighted above were related from data and information obtained from a Workshop held in May 2024 among ATGas, CTDUT, PipelineBrazil, Natran R&I and stakeholders from the hydrogen market. With effort, the mapping of 13 major topics was obtained, after being prioritized in five main topics, considered the most important and challenging points to be studied in relation to the transportation of H_2 in pipelines in Brazil. These points were considered the crucial points to ensure that the main problems and opportunities identified are adequately aligned with the results recorded and prioritized during the Stakeholder Workshop.

Abstract

This study reviews recent technical literature regarding the feasibility of repurposing natural gas pipeline infrastructure for methane-hydrogen blends. While leveraging current pipelines is vital for decarbonization, significant critical technological gaps remain. Key issues include metallurgical risks, specifically the difficulty of detecting hydrogen embrittlement mechanisms at the atomic and microstructural scales before structural failure occurs. Furthermore, differences in hydrogen compressibility, and diffusivity hinders the ability of inline inspection tools to accurately identify defects and degradation processes. These factors increase maintenance requirements and repair frequency. The analysis also highlights a significant lack of technical standards and specific regulations. Consequently, the study concludes that strategic R&D investment is essential to refine operation, inspection, monitoring and maintenance technologies and safely capitalize on hydrogen-driven decarbonization.

Some of the selected articles were presented as technical summaries during an event held on January 17, 2025. The subsequent debate addressed the challenges and opportunities related to the transition to a hydrogen-based economy and is summarized below under the five previously listed topics.

2.1 Integrity Monitoring

Transporting pure hydrogen (H_2) or blended with natural gas in existing pipelines presents technical and safety challenges due to the unique characteristics of hydrogen. Continuous monitoring of pipeline integrity is essential to prevent leaks, structural failures and explosion risks.

On the subject, professionals Rafael Almeida and Oscar Ruiz from the company Rosen [1], focused their presentation on the context of decarbonization, linked to the Paris Agreement and the RePower EU project, and warned about the risks of damage from inspection tools in PIG runs on pipelines containing H_2. However, they highlighted the economic opportunity of using existing pipelines, which can represent a cost of at least 30%, compared to the cost of new pipelines.

Another completed project, also undertaken by Rosen and Enbridge [17], explored the effects of hydrogen on pipeline system integrity in the face of limited data, using an approach centered around an extensive sensitivity study assessing fracture and fatigue. The approach also used an asset classification model based on the sensitivity study findings to support effective targeting of inspection and testing to maximize the value of the data collected. This was achieved by using deterministic approaches, QRA (Quantitative Risk Assessment), to assess and ultimately accept the levels of risk associated with reuse, including the impacts of hydrogen on failure acceptance.

In **[15]**, a sensor fusion system for in-situ measurement of H_2 mixture concentration was presented, combining ultrasonic and thermal conductivity (TC) sensors. To test this system, the sensors were installed in a pipeline together with pressure, temperature and humidity sensors to compensate for environmental factors, while mass flow controllers regulated the gas composition. Calibration across the entire range of H_2 concentrations confirmed the suitability of the ultrasonic and TC sensors for H_2 measurement. Using the system in the field will allow us to validate it and increase the data set, making the system even more accurate.

For the state of the art in the integrity assessment of H_2 pipelines [8], the YPP Vitor Hugo Marini cited the SafeH2Pipe project (JIP), funded by the Research Fund for Coal and Steel, which aims to understand the effect of mechanical damage and certain types of corrosion in hydrogen pipelines. With a direct focus on the combination of H_2 damage and regular pipeline damage, such as dents, grooves and third-party actions. It was highlighted that standards such as ASME B31.12 and API RP 1183 do not address H_2 damage, and there is a need for validation with tests in a real environment.

Furthermore, Engineer Mario Monteiro, summarizing 150 years of research on hydrogen embrittlement [5], highlights a significant deficiency in early detection of intrinsic interactions between hydrogen and materials at nano atomic scales and under in situ conditions. Focusing on the destructive methodology, at the nanometric scale, ATP (Atom Probe Tomography) that functions as a mass spectrometer to evaluate H_2 damage. The study points out the need to develop multimodal experimental techniques to comprehensively study hydrogen in materials.

Therefore, the main and most important challenges in the transportation of H_2 through pipelines found in the evaluated articles are:

- Hydrogen Embrittlement (HE): H_2 can penetrate the metal structure of pipelines, making them brittle and susceptible to cracking.
- Greater Permeability and Leaks: Since hydrogen has small molecules, it can escape through micro-cracks and inadequate connections.
- High Flammability and Explosivity: H_2 has a wide range of flammability in air (4% to 75%), increasing the risks in case of leaks.
- Differentiated Pressure and Flow Velocity: Hydrogen has a lower density than natural gas, requiring adjustments in pipeline pressure and flow to maintain transportation efficiency.

2.2 Risk and Change Management

Hydrogen (H_2) is considered a promising alternative for the energy transition, as it is a clean and abundant fuel. However, its use in infrastructures originally designed for other gases or fuels presents significant challenges and risks. One of the main problems is hydrogen embrittlement, a chemical phenomenon in which hydrogen penetrates metallic materials, such as carbon steel, making them brittle and susceptible to cracking. This can compromise the safety of gas pipelines, storage tanks and other industrial equipment. In addition, hydrogen has extremely small molecules, which makes it easy for it to diffuse and leak.

For the hydrogen transportation risk assessment in natural gas pipelines [9], YPP Rebecca Maciel presented the Analysis of the existing QRA (Quantitative Risk Assessment) methodology used for natural gas pipelines. The methodology aims to assess its suitability for use in pipelines transporting hydrogen and mixtures. By assessing risk management and prioritizing the quantitative methodology, it is observed that areas impacted by the leak are increased with the presence of H_2.

Modelling using probabilistic reliability, which systematically accounts for uncertainties, and provides a quantitative basis for reducing uncertainties as research progresses [13]. These were developed based on the most recent research on the adverse effects of hydrogen on pipeline material performance (i.e. hydrogen embrittlement). This was accomplished using empirical models that reflect the effects of hydrogen embrittlement on fracture toughness and fatigue crack growth rates. A demonstration analysis was conducted with the model to predict failure rates of a single crack type in a hypothetical pipeline.

Large-scale pipelines repurposing poses major challenges for operators in terms of safe change management. In ~~the~~ reference [16], repurposing was carried out through specific and in-depth asset analyses, considering operational, inspection, integrity and material aspects. For the conversion of the entire network, this means that these specific asset assessments must be carried out, which can be extremely time-consuming and expensive. The development of robust and simplified Management of Change (MoC) guidelines for identifying existing gaps and safe operational management during repurposing. Applicable in onshore transmission and distribution and in the offshore pipeline network.

For operational pipelines with 100% Hydrogen [10], the YPP Renan Leite presented the paper with operational simulation demonstrating graphs of better performance of PIGs for different operational conditions, and with speeds above 10m/s.

In summary, we can highlight that the main risks in adapting existing infrastructures are:

- Hydrogen Embrittlement – H_2 can penetrate metallic materials (such as carbon steel), making them brittle and increasing the risk of structural failure.
- Leakage and Diffusion – Due to its small molecular size, hydrogen can escape

through microcracks and connections, requiring enhanced sealing and monitoring.

- High Flammability and Explosivity – H_2 has a wide flammability range in air, making strict control essential to avoid ignition risks.
- Storage and Pressure – H_2 typically needs to be stored under high pressure or in a liquid state (-253°C), requiring strong tanks and piping.

And the main risk mitigation measures related in this study are:

- Material Integrity Analysis – Assessment of the compatibility of pipes, tanks and valves with hydrogen. If necessary, replacement with resistant alloys.
- Monitoring and Sensing – Implementation of specific sensors to detect leaks and monitor structural integrity.
- Safety Training and Procedures – Training teams to deal with the risks of H_2 nd updating emergency protocols.
- Leak Control – Use of more resistant seals and frequent inspections to prevent undetectable dispersion of the gas.
- Operational Tests and Risk Modeling – Conducting simulations and small-scale tests before the full implementation of hydrogen.

About the Management of Change for the use of existing infrastructure for H_2 [3], YPP Pedro Olm highlighted the effects of H_2 on the materials of the current system, the operational conditions and the impacts of H_2 on the inspection and maintenance of pipelines. In this presentation, it was emphasized that damage to the PIG due to the corrosive attack of H_2 should increase defects and, consequently, the repairs of these pigs.

In addition to what is mentioned in [3], the following points must be observed for the necessary operational changes:

- Infrastructure Modifications – Updating pipelines, compressors and storage systems to support H_2 without compromising safety.
- Gradual Blending with Natural Gas – Strategy to gradually adapt the existing network, minimizing risks and assessing impacts.
- Planning Transportation Routes – If H_2 is distributed through pipelines, it is necessary to review the route and reinforce safety at critical points.
- Creation of Specific Standards and Regulations – Implementation of technical and legal standards to ensure the safe and efficient use of hydrogen.

2.3 Corrosion protection

Measuring the proportions of hydrogen and its mixtures in pipelines requires specific sensors and devices to ensure accuracy and safety. As previously mentioned, hydrogen can cause embrittlement of metallic materials, making it essential to implement anti-corrosion protection measures in pipelines. Techniques such as high-performance internal coatings, the use of resistant materials such as stainless-steel alloys and polymers, and the application of diffusion barriers can minimize the effects of corrosion. In addition, continuous monitoring and preventive maintenance methods are essential to ensure the safety and durability of H_2 transport infrastructure.

On the topic of corrosion measurement and monitoring, when we thought about modernization plans during the transition to Hydrogen [4], YPP Levi Andrade raised the issue of impurities in Hydrogen and their potential impact. Hydrogen stored in depleted gas reservoirs can be contaminated with water, biological contaminants, H_2S and other impurities present on site. The article [4] cited the corrosion and embrittlement aspects. Considering the impurity aspect, it is technically preferable to use green hydrogen (produced through water electrolysis), as it typically contains fewer contaminants than blue hydrogen (produced via steam methane reforming with carbon capture), thereby reducing the risk of corrosion and material degradation in retrofitted pipelines. However, underground storage, even of green H_2, can reintroduce impurities.

Regarding the measurement and verification of the “internal linings” of the pipeline, YPP Luiz Eduardo Moraes mentioned the knowledge gaps regarding internal linings, based on polymers, ceramics, metals and composites [7]. The methodology presented included a comparative analysis of materials regarding hydrogen permeability, mechanical resistance and flow efficiency. There is no standardization and qualification for the topic of internal lining. Therefore, there is a real need to adapt the qualification methods for linings to include specific hydrogen parameters. In addition, the great importance of developing standards is evident. This point can be considered economically unviable because there is a lack of full-scale tests.

According to reference [13] the National Gas Transmission (NGT) presents its responsibility to develop the green energy system for the future, while meeting the. Due to its low ignition energy, wide flammability limits, and high diffusivity, H_2 poses unique risks compared to natural gas. Leak detection becomes more complex, as hydrogen is colorless, odorless, and flames are nearly invisible. Existing odorants used in natural gas may not perform effectively with H_2, requiring the development of new odorization standards. Regulatory bodies in the EU, UK, and US are updating codes to define acceptable blending ratios, testing protocols, and safety guidelines. Compliance with pressure vessel codes, pipeline integrity management, and occupational safety standards will be crucial before scaling up H_2 injection in national grids.

2.4 Limiting Factors for mixtures with H_2/CH_4

The mixture of methane (CH_4) and hydrogen (H_2) has gained prominence in the energy transition due to its potential to reduce carbon emissions and optimize the use of existing natural gas infrastructure. However, the incorporation of hydrogen into methane presents technical limiting factors of great importance that will be listed below.

2.4.1 Compatibility with Existing Infrastructure

One of the main limiting factors is the compatibility of CH_4-H_2 mixtures with natural gas transmission pipelines and equipment. Hydrogen has high diffusivity and can cause embrittlement in some metals, leading to cracks and leaks in carbon steel pipelines. Beyond pipelines, critical components such as valves, compressors, flanges, joints, and flow meters are directly affected by the presence of H_2, often requiring replacement with resistant alloys (e.g., austenitic stainless steels, nickel-based alloys, or high-performance polymers). Embrittlement is even more severe in welded joints and regions with residual stress. In some cases, the application of internal coatings or diffusion barriers may be necessary to reduce H_2 permeability.

2.4.2 Impact on Combustion Quality

The presence of hydrogen alters the combustion properties of natural gas. Hydrogen has a higher flame speed and lower ignition energy, which can cause combustion instability, increasing the risk of detonation in engines and turbines. Additionally, the H_2 flame is nearly invisible to the naked eye, which increases operational risks in industrial environments. The calorific value per unit volume is lower, requiring modifications to injectors and combustion chambers. Safety systems such as flame sensors and relief valves must be recalibrated to cope with the higher reactivity and the wider flammability range of H_2. Adaptations may also involve changes in combustion control software and post-combustion technologies to mitigate NOx emissions, which tend to increase at higher temperatures when hydrogen is used.

2.4.3 Mixture Limits and Calorific Value

The calorific value of hydrogen is significantly lower than that of methane, which can impact the energy efficiency of the mixture. The introduction of hydrogen reduces the energy density of the transported gas, requiring a larger volume for the same amount of energy. Studies indicate that mixtures with up to 20% hydrogen can be used in the current infrastructure without major modifications, but higher concentrations may require new technological adaptations.

2.4.4 Challenges in Measurement and Control

Measuring the flow rate and composition of CH_4-H_2 mixtures requires more sensitive and accurate equipment, since hydrogen has a lower molecular mass and different flow behavior compared to methane. Ultrasonic flow meters and specific sensors are required to ensure correct readings and avoid operational errors.

For the investigation of In-Line Inspection (ILI) tools, with the aim of achieving better quality of inspection data, in the article [12] the main elements to be considered in the inspection of hydrogen pipelines were presented, and the possible technological options to address problems such as internal and/or external corrosion, hydrogen embrittlement fatigue, geological risk, damage to third parties, material properties and morphology/appearance. The response of the ILI tool was defined and discussed in detail considering the compatibility of the materials of the inspection tool components. In addition to operational safety considerations, options to achieve better quality of inspection data were analyzed and developed.

2.4.5 Safety and Regulatory Standards

Hydrogen has a higher risk of leakage due to its low viscosity and high permeability, in addition to having a wide range of flammability in air. Regulations for CH_4-H_2 mixtures are still under development in several countries, seeking to ensure safety standards in operation, storage and transportation.

Within this context of regulatory standards, in reference [11], the author presents a Consensus of Engineering Requirements - CERs for hydrogen pipelines with the main objective of updating to ASME B31.12, especially in relation to the technical standards for conversion and operation of hydrogen pipelines and hydrogen blending. The CERs will be processed through ASME for approval, and inclusion in the 2026 version of ASME B31.8. And thus become the international standard for hydrogen transmission and distribution pipelines.

When we refer to the topic of mixing, the author of the reference [6] mentions the mixing of H_2 and NG, by the direct introduction of hydrogen into large diameter and high-pressure gas transmission pipelines [6]. In this article, the author presented a computational analysis, using Computational Fluid Dynamics (CFD) for a hydrogen mixing target of 4.8–20% volume fraction, a limit supported by the UK government, in the national gas distribution network. The study addresses direct and indirect mixing in the pipeline, and their limitations, but suggests new tests with changing the position of injector nozzles, for CFD simulation.

2.5 Economic aspects for repurposing pipelines

There are several economic aspects related to the use of H_2 in existing pipeline networks designed to transport natural gas. As in reference [2], the Engineer Alexandre Figueiredo presented the economic aspects of using H_2. At that time, the number of citations of the topic H_2 in the annual reports of oil companies around the world was highlighted, indicating a growing interest and investment in the topic. The company with the most citations was the French company Total Energies.

The main economic aspects related to this mixture are highlighted below:

2.5.1 Infrastructure and Adaptation Costs

The use of H_2 and CH_4 mixtures requires adaptations to existing infrastructure. Although natural gas distribution networks can transport small percentages of hydrogen (typically up to 20%), larger concentrations may require significant modifications to pipelines, compressors. End-user appliances such as burners, boilers, and turbines may also need redesign or replacement to handle higher H_2 concentrations safely. The cost of adaptation depends not only on the hydrogen percentage but also on factors such as material compatibility, geographic extension of networks, and safety compliance requirements. In some regions, retrofitting may be more expensive than building dedicated hydrogen pipelines. The cost of these adaptations depends on the percentage of H_2 mixed and the extent of the infrastructure required.

2.5.2 Production Cost and Competitiveness

The cost of producing hydrogen varies depending on the method used. "Grey" H_2, produced by steam reforming of methane, is cheaper but generates CO_2 emissions. “Green” H_2, obtained via electrolysis with renewable electricity, is more expensive but environmentally sustainable. However, as technology advances and renewable energy costs fall, the competitiveness of green hydrogen is likely to increase.

2.5.3 Impact on Natural Gas Prices

The integration of hydrogen into natural gas systems may influence final energy prices. In scenarios where hydrogen production is subsidized or benefits from fiscal incentives, blending could lower consumer costs. However, in most current contexts, the higher cost of hydrogen compared to natural gas leads to an overall increase in blended gas prices when subsidies are absent. Price impacts also depend on regional energy markets: in liberalized markets, costs are often transferred directly to consumers, while in regulated systems, governments may buffer increases through policy instruments. Additionally, price volatility of renewable electricity and carbon credits will affect the competitiveness of hydrogen-enriched gas.

2.5.4 Sustainability and Government Incentives

Governments around the world have created incentives for the adoption of low-carbon fuels, such as subsidies, carbon credits and funding for research and development. Examples include the European Union’s Hydrogen Strategy, the U.S. Inflation Reduction Act with production tax credits, and Japan’s and South Korea’s hydrogen roadmaps. Incentives not only aim to reduce costs but also to de-risk investment, support pilot projects, and create market demand through quotas and mandatory blending targets. The long-term sustainability of these measures depends on consistent policy frameworks and international cooperation. Without stable regulation, investors may hesitate to finance large-scale hydrogen projects.

2.5.5 Potential Emissions Reduction and Benefits for Industry

Adding hydrogen to methane reduces the carbon footprint of the final fuel, allowing industries that rely on natural gas to reduce their emissions without drastic changes to their processes. Blending hydrogen provides a transitional pathway for hard-to-abate sectors such as steel, cement, and chemicals, where electrification is not yet viable. Industries adopting hydrogen-enriched natural gas may gain access to green financing, preferential trade agreements, and enhanced corporate reputation in ESG (Environmental, Social, and Governance) reporting. Moreover, the reduction in direct CO_2 emissions can help meet international decarbonization commitments (e.g., Paris Agreement) and prevent exposure to carbon border adjustment mechanisms.

3. Conclusion

This research presented clearly delineates the critical technical and operational challenges inherent in the transition to hydrogen (H_2) as a major energy vector, particularly within existing pipeline infrastructure.

Our findings underscore three fundamental hurdles that require immediate and concerted R&D focus:

- Material Integrity and Compatibility: The paramount challenge remains the effective management of hydrogen-induced degradation, requiring the development and qualification of materials resistant to $_{H2}$ embrittlement under high-pressure pipeline conditions.
- Operational Assurance: A comprehensive transition necessitates the creation of novel inspection and maintenance techniques specifically adapted to $_{H2}$ service, including enhanced leak detection and integrity management protocols.
- Regulatory Framework: The current lack of specific standards, regulations, and certification pathways constitutes a significant non-technical barrier that must be addressed through collaborative industry and government action.

Crucially, the successful and secure deployment of H_2 blending and transport relies on the robust integration of advanced risk management methodologies coupled with a strategic evaluation of necessary operational and design modifications. These measures are indispensable for ensuring a safe and efficient migration toward this new energy matrix.

The long-term economic viability of H_2 blending is intrinsically linked to two external drivers: the accelerating demand for sustainable energy solutions, often propelled by government incentives and favorable policy, and the evolution and cost reduction of H_2 production technologies. Ultimately, overcoming the identified technical gaps—supported by a proactive regulatory landscape—will determine the timeline and scale of Hydrogen's successful global integration.

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