Journal of Geoscience and Environment Protection, 2024, 12, 70-94
https://www.scirp.org/journal/gep
ISSN Online: 2327-4344
ISSN Print: 2327-4336

Green Hydrogen: Perspectives and Challenges in Using the Natural Gas Network in Ceará/Brazil

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How to cite this paper: de Castro, F. A., de Oliveira, M. L. M., de Lima, L. C., & Serra, D. S. (2024). Green Hydrogen: Perspectives and Challenges in Using the Natural Gas Network in Ceará/Brazil. *Journal of Geoscience and Environment Protection, 12,* 70-94.
https://doi.org/10.4236/gep.2024.123005

Received: December 2, 2023
Accepted: March 19, 2024
Published: March 22, 2024

Abstract

Climate change, mainly caused by the use of non-renewable fuels, has raised global concerns and led to the search for less polluting energy sources, making hydrogen a promising energy alternative with the potential to contribute to changes in the energy mix of various countries through the use of technologies that enable its production and use with low or zero carbon emissions. In this context, Brazil has aroused great interest from other countries in exploring its renewable resources for the production of hydrogen (green hydrogen). In this sense, the use of natural gas pipelines and the use of hydrogen in mixtures with natural gas have become the subject of studies due to their economically viable alternative for the immediate use of this energy vector. However, there are still technical and regulatory challenges regarding the integration of hydrogen into the existing natural gas pipeline network. In this context, the present study aims to address the effects of hydrogen interaction with the structure of natural gas pipeline steel and the regulatory barriers to the use of this network for the transportation of green hydrogen, particularly in the state of Ceará/Brazil. After extensive analysis of literature and regulatory documents, it was concluded that: 1) Ceará/Brazil has strong potential to meet the demand for green hydrogen through the use of solar and wind energy sources; 2) there is feasibility for the adaptation or conversion of natural gas infrastructure for the transportation of green hydrogen; 3) discussions regarding the regulatory competence of green hydrogen transportation and distribution through the natural gas network in Brazil are still incipient; 4) the current regulation of the natural gas industry can serve as a subsidy for the regulation of green hydrogen and natural gas transportation.

Keywords

Decarbonization, Natural Gas, Green Hydrogen, Pipelines

1. Introduction

The escalating demand for energy, concerns about the possible depletion of non-renewable resources, environmental impacts of industrial processes using fossil fuels, and the urgency of addressing climate change have prompted global discussions on alternatives. The overarching theme revolves around exploring non-polluting and renewable energy sources (Simões-Moreira et al., 2017).

Human utilization of nature and primary energy sources, transformed into secondary energy for diverse end uses, has led to environmental challenges. Present society faces the mission to overcome, mitigate, and eliminate these issues (Simões-Moreira et al., 2017). Recognizing the priority of the environmental component has driven global initiatives for sustainable energy development.

The COP 21 in Paris (2015) emphasized the goal to limit the global temperature increase to below 2˚C by 2050, with efforts to restrict it to 1.5˚C, referencing pre-industrial era values (Reis, Fadigas, & Carvalho, 2012). All human activities affecting the planet's environment and climate are primarily linked to energy source exploitation.

In Brazil, the National Energy Balance - Summary Report (EPE, 2022) indicates a 12.4% increase in CO_2 emissions associated with the energy matrix from 2020 to 2021. The rise to 445.4 million tons of CO_2 equivalent in 2021 underscores the direct connection between energy production, consumption processes, climate change, and greenhouse gas emissions.

Comprehensive attention to the energy sector is crucial, addressing both specific and global issues. This involves adopting strategies for sustainable energy systems, considering innovations, technological advancements, and significant global changes (EPE, 2022).

Strategic actions can align energy planning with low-carbon activities, emphasizing increased use of renewable sources. Renewable energy, sourced from naturally replenished processes or human-intervened regeneration, includes hydropower, wind, solar, and biomass energy, playing a growing role in global energy matrices (Corrêa et al., 2020).

Concurrently, scientific efforts towards a carbon-free economy focus on hydrogen as an alternative energy carrier. Hydrogen, a key player in sustainable energy transition, requires the development of reliable and safe transport systems. Considering the potential of natural gas pipelines, hydrogen could leverage existing infrastructure, removing barriers in the hydrogen economy (Simões-Moreira et al., 2017).

In the pursuit of global decarbonization outlined by energy policies, Ceará, a state in Brazil, stands out for its favorable geographical location with abundant wind and solar resources. It emerges as a key player in implementing green hydrogen production projects, especially for countries with a hydrocarbon-dominated energy matrix.

The 2031 Decennial Energy Expansion Plan (PDE 2031) outlines industrial-scale green hydrogen projects in Brazil, including the Green Hydrogen Hub in Ceará's Port of Pecém, projects in Pernambuco's Port of Suape, and projects in Rio de Janeiro's Port of Açu. These projects are currently undergoing technical and economic feasibility studies (MME/EPE, 2022).

In addition to using natural gas pipelines, transport in the form of ammonia is considered attractive for intercontinental shipping, particularly in maritime mode (BLOOMBERGNEF, 2020). However, the ideal scenario would be the construction of new infrastructure for the movement of pure hydrogen, but in cases where it is possible to reuse the existing gas pipelines for natural gas (for example, North America, Europe, or East China), investment costs can be 65% - 94% lower than the cost of new infrastructure (Machado, 2022).

In this context, the use of natural gas pipelines for the movement of green hydrogen has been a recurring theme in academic studies and research in the energy sector, and the purpose of this study is to address the effects of hydrogen interaction with the structure of natural gas pipelines and the barriers to regulation of the use of this network for the movement of green hydrogen. Both themes play an important role in the hydrogen economy, given that the weakening of the steel structure can cause irreparable damage to the pipeline if measures are not taken to minimize this effect. Regulation, in turn, represents the legal security that investors and users expect to ensure the balance in the contractual relationship and the expected benefits for both parties.

2. Methodology

The purpose of this article is to present the current situation regarding the utilization of natural gas infrastructure for the movement of green hydrogen, addressing conceptual, technical, and regulatory aspects, as well as discussing its potential contributions and challenges for the decarbonization of this sector. The analysis and evaluation of the information in this study aimed to answer the following questions:

1) Does Brazil and the state of Ceará have potential in renewable energy sources for the production of green hydrogen?

2) What are the challenges in utilizing natural gas infrastructure for the movement of green hydrogen?

3) Who holds the regulatory competence in Brazil for the injection of green hydrogen into the natural gas network?

4) Can the regulation of the natural gas industry in Brazil be used as an initial basis for the regulation of green hydrogen?

The methodology used in this study is characterized as descriptive, exploratory, and qualitative. It was conducted through the analysis of publications related to the subject. The study also includes the analysis and evaluation of reports, regulations, and technical notes from official bodies and publications of companies operating in the hydrogen sector.

The research structure follows the following sequence: The introduction and methodology used are presented in Sections 1 and 2, respectively. Section 3 describes the technologies employed in the production of green hydrogen. The infrastructure of natural gas that can be used for the movement of green hydrogen and the technical challenges are addressed in Section 4. Results and discussion are the focus of Section 5, concentrating on the analysis of the regulatory model for the injection of green hydrogen into the natural gas network. Finally, conclusions and suggestions are provided in Section 6.

3. Hydrogen and Its Technologies

Hydrogen emerges as a transformative opportunity in the global energy matrix, allowing for a gradual reduction in dependence on fossil fuels. With various production and usage options and recognized for its low or zero emission of polluting gases (Farmer, 2020), hydrogen becomes a priority for countries aiming for sustainable economic development. In addition to representing a new energy paradigm as the lightest and most ubiquitous element in the universe (Witstok, 2022), hydrogen, when converted into energy, becomes an abundant source that does not deplete and does not emit CO_2.

Despite its rare occurrence in nature in a pure state, requiring extraction from natural sources (Rifkin, 2003), H_2 stands out for its versatility, finding applications in various industries such as refineries, the chemical industry, steel production, the food industry, internal combustion engines, and fuel cells (Teoh et al., 2023; Mohideen et al., 2023; Seyam, Dincer, & Ibrahin, 2023; Chen et al., 2023a). Considering the increasing greenhouse gas emissions (GHG), hydrogen is the subject of studies and projects as an energy vector capable of replacing fossil sources. Its ability to store energy, especially from renewable sources such as wind and solar (Noyan, Hasan, & Pala, 2023), stands out as a solution to the intermittency in the electrical generation of these sources.

3.1. Hydrogen Sources

Hydrogen, considered a secondary source of energy, is widely favored in the renewable energy scenario (Souza, 2009). Found in fossil compounds, biomass, or water, hydrogen requires complex processes for extraction, involving the breaking of hydrocarbon chains or disassociation of water molecules (Abdalla et al., 2023). Production methods, predominantly based on fossil fuels, generate CO_2 emissions, with steam methane reforming (SMR) being the most economical and globally used (Chen et al., 2023b). Nevertheless, alternatives such as water electrolysis and studies on innovative sources, such as green algae and natural hydrogen, offer more sustainable prospects (Hren et al., 2023; Lora & Venturini, 2012).

The challenges of hydrogen production include the need for energy from primary sources, as well as subsequent stages such as storage, transportation, and distribution, with natural gas infrastructures being a viable option (CNI, 2022).

The current production, mainly linked to natural gas and coal, significantly contributes to global CO_2 emissions (Zhiznin et al., 2023). Strategies like carbon capture and utilization (CCUS) and the use of biomass in pyrolysis or gasification processes offer more sustainable alternatives, promoting carbon neutrality or even negativity (Yue et al., 2023; Mishra et al., 2023; Wu, Lan, & Yao, 2023).

Despite the challenges, hydrogen remains a promising energy source, with its potential being explored on various fronts, from electrolysis to innovative sources like green algae and natural hydrogen (Hren et al., 2023; Lora & Venturini, 2012). The search for more sustainable methods in hydrogen production and usage reflects the urgency to reduce CO_2 emissions and move towards a cleaner and more efficient energy matrix.

3.2. Hydrogen Production Routes

Hydrogen production involves various pathways, with two crucial stages: the selection of the source or raw material and determining the primary forms of energy for extraction, which can be renewable or non-renewable. Established technologies, such as steam methane reforming of natural gas and coal gasification, coexist with emerging methods, including photochemical and biological approaches. Some processes incorporate steps for the capture, storage, and utilization of CO_2, characterizing hydrogen as "blue" (Ajanovic, Sayer & Haas, 2022).

The classification of hydrogen is based on the raw material, the production process, and CO_2 emissions, following a color-coded scheme referenced in **Figure 1**, facilitating communication about the type of hydrogen in studies (MME, 2022). Currently, the majority of hydrogen comes from fossil sources, classified as "gray," "black," or "brown," resulting in significant CO_2 emissions, contradicting net-zero emission goals (IRENA, 2022).

The choice of the production pathway depends on the desired quantity and purity of hydrogen. Primary technologies require energy sources, both fossil and renewable. The combination of thermochemical, electrochemical, and biological processes results in secondary fuels, undergoing catalytic transformations for the final production of hydrogen (Lora & Venturini, 2012). Each pathway requires a specific energy source, emphasizing the importance of biochemistry, thermal, and photonic processes in extraction, as illustrated in **Figure 2**, representing the main technological pathways for hydrogen production from fossil and renewable sources (Vaz, 2021).

3.3. Hydrogen Production Capacity: The Brazilian Scenario

In the context of green energies, Brazil emerges as a potential producer of green hydrogen, especially due to its considerable potential for generating electrical energy from renewable sources, particularly photovoltaic solar and wind energy. The installed capacity for electrical generation reached 190 GW in 2022, with wind and photovoltaic solar contributing 12.94% and 4.08%, respectively, and future projects adding more than 91 GW (ANEEL, 2023). The significant growth

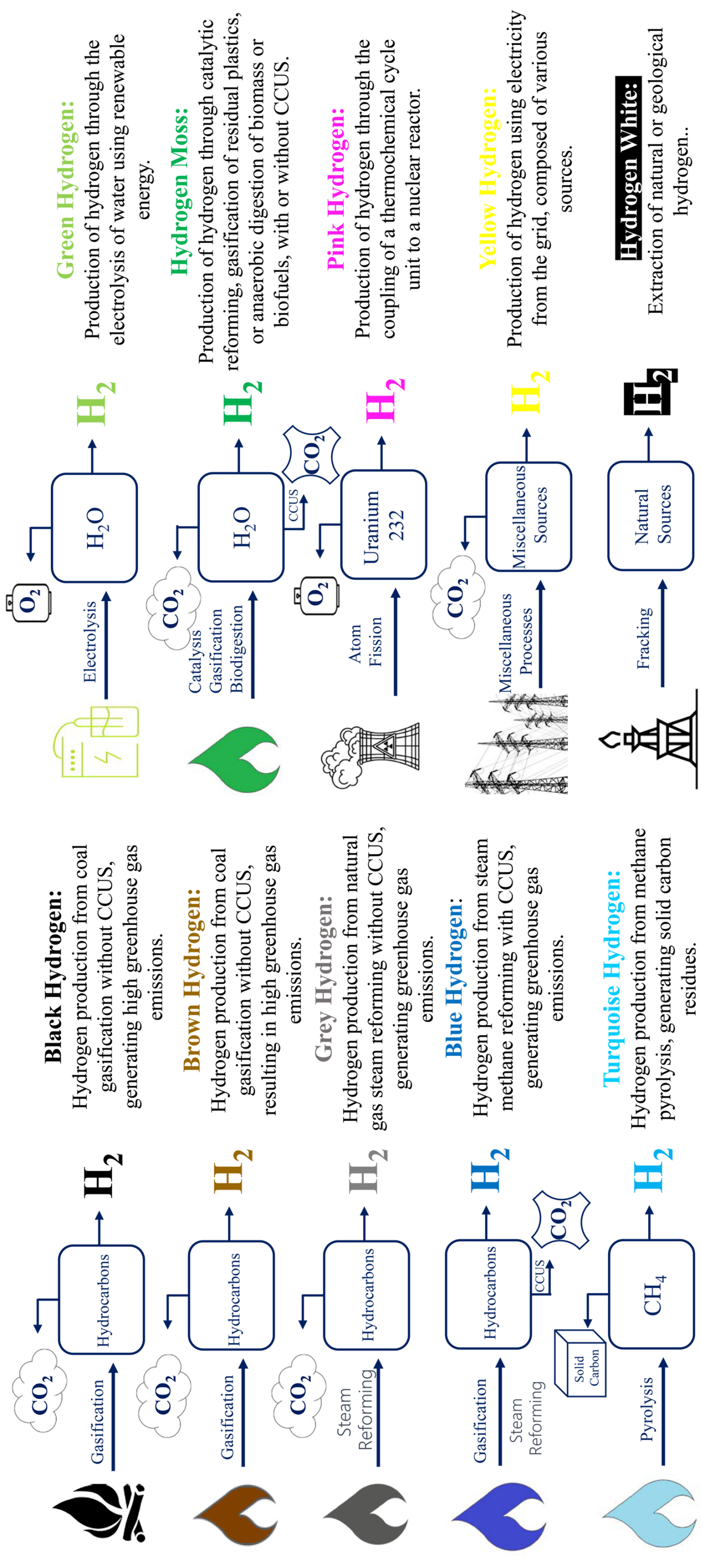

Figure 1. Hydrogen classification on a color scale.

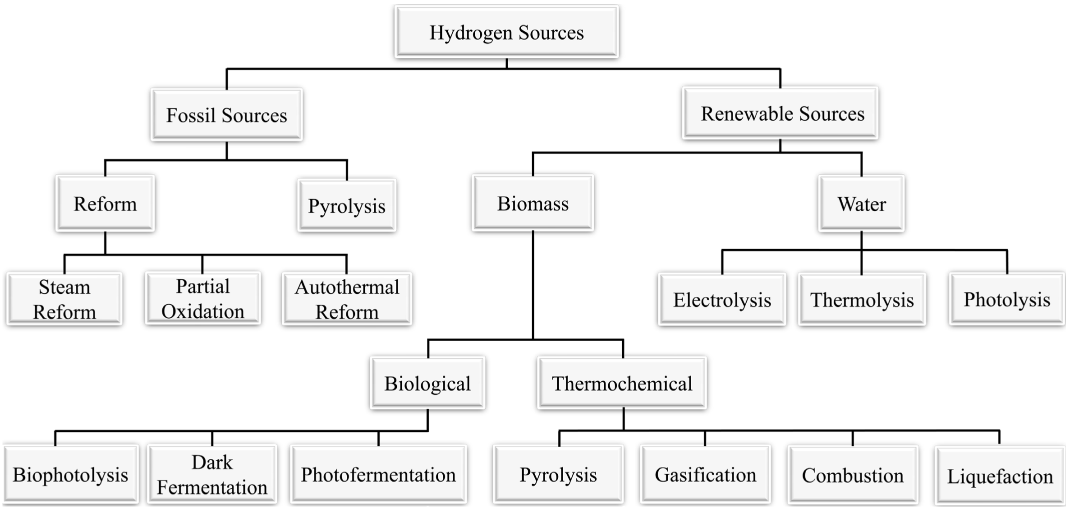

Figure 2. Technological routes for hydrogen production.

Table 1. Electricity generation in Ceará in 2023.

Primary Energy	In Operation	Under Construction	Not Started	Power Granted (kW)	Power Inspected (kW)	Power Inspected (%)
EOL	100	3	49	4,677,340.00	2,577,840.00	48.18
UFV	31	9	167	8,463,056.00	708,956.00	13.25
UTE	30	-	1	3,635,576.10	2,063,688.10	38.57
Total	161	5	196	16,755,972.10	5,350,484.10	100

Electricity generation capacity in Ceará. EOL = Wind power plant; UFV = Photovoltaic Solar Generator Center; UTE = Thermoelectric plant.

of these sources in recent years, with an 85.6% share in 2022, highlights the robustness of the sector, with the state of Ceará, having an estimated potential of 1363.2 TWh/year in wind and solar energy, being a prominent player in this movement (CCEE, 2022; Associados, 2019). With a current installed capacity of over 5 GW, Ceará demonstrates alignment with the transition to green energies, presenting a favorable scenario to drive the green hydrogen industry (ANEEL, 2023).

Table 1 illustrates the installed capacity for electrical energy generation in the state of Ceará, where wind energy represents 48%, thermal power plants 38.57%, and photovoltaic solar 13.25%, with a forecast of an additional approximately 8 GW in the coming years (ANEEL, 2023). This landscape reinforces Brazil's, especially Ceará's, position as a promising player in green hydrogen production, benefiting from the transition to renewable sources and a conducive environment for the sustainable growth of the green hydrogen industry.

4. Natural Gas Infrastructure and the Possibility for Moving Mixtures with Green Hydrogen

The natural gas industry, considered a network industry, resembles sectors such as electric power, railways, telecommunications, and sanitation. Natural gas goes through a production chain from extraction to the distribution networks of state concessionaires, utilizing a network infrastructure to reach the end consumer. The possibility of blending hydrogen with natural gas provides an expansion opportunity for the hydrogen industry, leveraging existing infrastructure. Governments and concessionaires worldwide are exploring the injection of hydrogen into natural gas pipeline networks as a strategy to reduce CO_2 emissions (Arends, 2020).

Despite the advantages, analyzing the differences between natural gas and hydrogen highlights safety issues due to the distinct physical properties of these gases. Hydrogen transportation can occur in various forms, such as gas, liquid, or derivatives, using roads, ships, or pipelines. Adapting existing natural gas infrastructure to store, transport, and distribute hydrogen is a complex challenge, requiring a thorough review of production methods, storage, transportation, and efficient final applications for hydrogen (Gondal, 2019; Cerniauskas et al., 2020; Wu et al., 2022). A pragmatic approach to transitioning to a hydrogen economy would involve initially using existing infrastructure to transport natural gas-hydrogen blends, followed by progressive operational modifications and the gradual replacement of fossil sources (Mahajan et al., 2022).

In Brazil, where natural gas infrastructure is under development, the potential use of 9409 km of transport pipelines and 38,620 km of distribution network to transport hydrogen is a strategic consideration. The state of Ceará stands out in this scenario, with a distribution infrastructure of about 514.2 km, enabling the harnessing of green hydrogen production potential and promoting the regional development of the natural gas industry (Dodds & Demoullin, 2013; MME, 2021a; CEGÁS, 2022).

4.1. Technical Challenges of Transport and Distribution

Governments and private initiatives globally are exploring projects to inject hydrogen into natural gas transportation and distribution pipelines, aiming to decarbonize this sector and reduce greenhouse gas (GHG) emissions. Challenges such as equipment adaptation and potential changes in the amount of energy supplied to users need to be overcome, and studies are underway to address these issues (Dodds & Demoullin, 2013). The United Kingdom provides a practical example of this concept, considering the conversion of the currently supplied natural gas to users to hydrogen as a strategy for decarbonizing residential heating (Dodds & Demoullin, 2013).

The Power-to-Gas (P2G) concept stands out as a technological solution to contribute to decarbonization by integrating renewable energies. The European Commission includes natural gas as a key component in its strategy to implement a hydrogen economy, leveraging existing infrastructure to transport and store hydrogen (Quarton & Samsatli, 2018; Pellegrini, Guzzini, & Saccani, 2020). However, due to the specific properties of hydrogen, the integrity of the natural gas network is a concern, requiring detailed assessments of gas transportation and distribution systems, considering factors such as geographical location, maximum hydrogen concentration in the mixture, and end applications (Vidas, Castro, & Pires, 2022).

In the research and testing scenario for hydrogen and natural gas mixtures, two paths are considered: the direct injection of green hydrogen into the network or the transfer to a methanation processing unit for synthetic natural gas production. The choice between these paths depends on the project's objectives, but both options require detailed studies due to the effects of hydrogen interaction with pipeline materials (Pellegrini, Guzzini, & Saccani, 2020). Despite challenges and necessary modifications, the hydrogen mixture in the natural gas pipeline presents a practical solution to boost systems based on large solar and wind parks, with the potential to reduce investments compared to building new hydrogen pipelines (Kovac, Paranos, & Marcius, 2021). In addition to reducing GHG emissions, the use of pure hydrogen downstream in the network, in applications such as automotive or stationary fuel cells, represents an additional perspective for energy transition (Chen et al., 2022; Linde Engineering, 2023).

4.1.1. Effects of Hydrogen on the Structure of Natural Gas Pipelines

Hydrogen, due to its physical properties, can have significant impacts on the structure of natural gas pipeline materials, with hydrogen embrittlement (HE) being one of the main phenomena. This phenomenon involves chemical and physical processes that result in the progressive and permanent loss of the metal's deformation capacity. HE can occur due to the accumulation of hydrogen in various locations within the microstructures of the pipeline material, causing changes in residual stress states and facilitating failures even at stress levels below the material's yield limit (Li et al., 2023; Hoschke et al., 2023).

The mechanisms explaining hydrogen embrittlement include hydrogen enhanced decohesion (HEDE), localized plasticity mechanisms (HELP), and adsorption-induced dislocation emission (AIDE). Although these theories differ, they all assume that embrittlement occurs from a minimum concentration of hydrogen in the metal's crystalline lattice, known as the critical concentration (Santos, Maciel, & Sanatana, 2022). Mechanisms like HEDE involve the expansion of the metal's crystalline lattice due to dissolved hydrogen, resulting in reduced tensile strength and facilitating fractures. HELP, on the other hand, relies on hydrogen's ability to increase the movement of dislocations, leading to localized plastic deformation and crack nucleation (Santos, Maciel, & Sanatana, 2022; Kholtobina et al., 2021).

The interaction of hydrogen with metals occurs when atomic hydrogen diffuses into the metal, traversing the crystalline structure through interstitial sites. During this process, hydrogen can be trapped in various types of defects, such as grain boundaries, voids, and dislocations, influencing the material's properties (Dos Santos & Biehl, 2014). Metal properties, such as diffusivity, solubility, and permeability, are essential factors in understanding hydrogen interaction and its consequences. Different types of interaction can lead to various structural failures, such as loss of ductility, internal flaws, and macroscopic damage (Sun & Cheng, 2021).

Understanding the interaction of hydrogen with metals is complex, requiring consideration of the diversity of trapping sites and variables involved. Experimental techniques, such as temperature-programmed desorption, electrochemical permeation testing, and multiscale simulation, are employed to study hydrogen interaction in the microstructure of metals, providing essential data for characterization and minimization of hydrogen-induced damage (Filgueiras, 2019).

4.1.2. Influence of Hydrogen and Natural Gas Mixture Concentration on Transport and Distribution Conditions

The impacts of hydrogen on pipelines go beyond materials, affecting the flow state of the mixed gas, constant pressure drop, and the amplitude of transient pressure shock in the pipeline. To prevent damage, the hydrogen content generally should not exceed 30% (Chen et al., 2022). The movement of the hydrogen and natural gas mixture requires careful monitoring due to the different characteristics of each component. Natural gas, containing hydrogen sulfide, contributes to corrosion, while the difference in flammability range between hydrogen and natural gas must be considered (Laureys et al., 2022). The analysis of movement effects should cover physicochemical characteristics and operational variables such as pressure, temperature, and additives in the mixture.

Elements of control and measurement infrastructure, such as analyzers for odorant concentration, are crucial. Issues in their operation caused by the increased hydrogen content imply harmful impacts on the operability and safety of gas users. The pressure of hydrogen gas affects the sensitivity to embrittlement of steels for pipelines, with considerations for changes in the ductility of the steel tube with a slight loss of yield strength (Laureys et al., 2022; Li et al., 2022). The movement of the mixture, usually operating at constant pressure, generates static and cyclic mechanical loads, influencing the ductility and yield strength of the tube (Xing et al., 2019).

Temperature is a determining factor in the interaction of hydrogen with metals, affecting surface reactions, solubility, and diffusivity. Gas compression is essential for movement, crucial for the activity's development to the final destination. The temperature increase reduces the gas density, and measures such as burying and isolating the network minimize heat losses, despite higher investments and maintenance costs. Gas compression in the hydrogen and natural gas mixture is critical, indicating the use of reciprocating and centrifugal compressors. The measurement of the transported gas volume is affected by the combination, with studies highlighting changes in thermophysical properties (Witkowski et al., 2018; Dell'isola et al., 2021).

Odorizing natural gas is vital to ensure safety in pipeline networks. Test results indicate that a hydrogen content of up to 15% does not interfere with the odorant substance tetrahydrothiophene (THT), but long-term stability should be considered (Huszal & Jaworski, 2020). The report for the British Health and Safety Executive (HSE) indicates that the introduction of hydrogen into the gas network does not affect the odorization process up to a percentage of 20% (Huszal & Jaworski, 2020). In Brazil, natural gas follows the specifications of the National Agency of Petroleum, Natural Gas, and Biofuels (ANP) until specific regulations for hydrogen or its mixture with natural gas are implemented (ANP, 2008).

4.1.3. Influence of Hydrogen and Natural Gas Mixture Concentration in Network Installations and End Use

The mixture of natural gas with hydrogen implies changes in the physical and thermal properties of the blend, with variations in the speed of sound, relative density, calorific value, and Wobbe index. In concentrations of up to 10% hydrogen, no component replacements are necessary, allowing the maintenance of operational practices in gas transportation, distribution, and final consumption systems, although additional investigations are suggested for higher hydrogen contents (Witkowski et al., 2018; Dell'isola et al., 2021).

The use of lower volumes of hydrogen (<10%) involves minimal adjustments to the natural gas network and its end-users, while an increase in hydrogen supply can reduce costs and encourage applications with higher decarbonization potentials. However, higher concentrations may require changes due to impacts on pipeline steel and potential damage to burners (MME, 2022).

The application of hydrogen in hard-to-decarbonize industries, such as steel production, has specific limitations. In the aviation sector, synthetic fuels derived from hydrogen can be blended in higher proportions. Studies indicate that a mixture of 30% hydrogen by volume in natural gas does not cause changes in pipeline materials, but limitations are observed in compressed natural gas (CNG) vehicle steel tanks (Griffiths et al., 2021; Vidas, Castro, & Pires, 2022).

Studies initiated since the 1980s suggest that blends of low concentrations of hydrogen with natural gas (5% - 15% H_2 by volume) are feasible and safe, without significantly increasing risks or causing potential damage to end-use devices such as appliances. Adaptations in the end-use system are necessary at higher mixture levels, and concentrations of up to 28% hydrogen can be safely used in existing household installations with proper maintenance for appliances designed for natural gas (Ogden et al., 2018; NREL, 2013).

4.1.4. Definition of Hydrogen Limits in the Concentration of the Mixture

The definition of regulatory standards to determine safe limits for introducing hydrogen into natural gas networks is at different stages of development in various countries. Studies in this area aim to establish appropriate and permissible ranges of hydrogen in the mixture, ensuring the safety of the network. This approach requires consideration of the conditions present in the networks for the safe movement of hydrogen and the assessment of the gas's impact on fuel properties, including combustion and the control and measurement infrastructure of the equipment (Huszal & Jaworski, 2020).

Studies have focused on defining these ranges, taking into account variables such as pipeline structure, pressure, temperature, equipment suitability, operational safety, among others. In Germany, for example, a comprehensive study was conducted on the limits of hydrogen blending in various equipment and components of the natural gas system. The results indicated that gas turbine compressors and Compressed Natural Gas (CNG) vehicle tanks require modifications at specific hydrogen concentrations, highlighting the complexity in determining limits without detailed knowledge of the system's characteristics (MME, 2022; ANP, 2008; Bard et al., 2022).

Current regulations in European natural gas networks set concentration limits for hydrogen between 0.1% and 12% by volume. The application of these limits depends on the specifics of each natural gas system, impacting the amount of hydrogen energy transported in the network. Results from projects such as NaturalHy show that concentrations of up to 20% hydrogen do not result in gas separation in the mixture and present explosion risks similar to natural gas. The study also demonstrated the compatibility of materials such as polyethylene (PE) and polyvinyl chloride (PVC) up to this concentration (Ogden et al., 2018; Wang et al., 2022).

Research from the National Institute of Gas Technology in Poland (INIG-PIB) established safe maximum levels of hydrogen for addition to methane-rich natural gas, considering factors such as system element strength, operational safety, and accurate meter readings. These levels vary between 8% and 36%, depending on legal specifications, combustion safety, and the efficiency of end devices (Huszal & Jaworski, 2020).

Several research efforts address the implications of hydrogen blending in different sectors and applications. Projects like NaturalHy in Europe and HyDeploy in the UK conduct practical tests with hydrogen and natural gas blends in private and public networks. These studies reveal the technical feasibility of blending up to 20%, with no negative impacts on infrastructure materials or end devices such as boilers and stoves (Witkowski et al., 2018; Ekhtiari, Flynn, & Syron, 2022; HyDeploy, 2020).

Considering specific characteristics such as flame length, temperature, and emissivity in industrial applications, the viability of hydrogen in the blend is discussed. Below 10% concentrations, the impacts on properties are insignificant, but for higher mixtures, such as 15% to 50%, additional considerations are needed, including equipment conversion and increased compression capacity (Davis et al., 2023).

Governments plan to inject renewable hydrogen into natural gas networks to reduce emissions, leveraging existing infrastructure. This strategy is seen as a first step toward a hydrogen economy, offering benefits such as creating a market for surplus renewable energy and reducing the carbon content in gas. The literature reviewed emphasizes the ongoing need for research and adaptations in codes and standards to incorporate natural gas and hydrogen blends, with ranges of 5% to 20% considered in the literature (Xing et al., 2019; Laureys et al., 2022).

5. Results and Discussion

This section analyzes and discusses the results examined in the literature, seeking to reach an understanding of the variables involved in leveraging the natural gas infrastructure for the transport of pure hydrogen or its mixture with natural gas. It explores potential technical limitations in the current transportation and distribution networks of natural gas, considering the effects of hydrogen interaction with the pipeline structure leading to steel embrittlement. Additionally, it addresses impacts on operational variables, influence on gas flow meters, and potential alterations to network and end-use equipment. The section also delves into current regulatory perspectives, aiming to serve as a foundation for agencies and governments seeking to implement rules for the movement of hydrogen and natural gas blends. The analysis considers questions regarding the jurisdiction responsible for establishing rules and standards for this activity.

5.1. Challenges in Defining the Brazilian Regulatory Model

Hydrogen, whether as a fuel or raw material, has been a subject of study for some time, gaining prominence in the global energy sector with the advancement of technologies for decarbonization. However, the definitive implementation of its production chain requires substantial investments, with the essential need to ensure legal certainty to attract investors. In Brazil, regulatory discussions regarding the use of hydrogen as an energy source are in the early stages, sparking debates about defining regulatory authorities, the necessity of specific regulatory frameworks, and the establishment of technical standards. Creating clear regulatory conditions is crucial to provide stability and security to investors, signaling a safer approach in environmental and tax terms (MME, 2020).

The National Energy Plan 2050 (PNE 2050) highlights hydrogen as a disruptive energy that will significantly transform the energy market. However, standardizing the hydrogen industry in Brazil faces challenges, including defining a regulatory framework, rules for hydrogen battery storage and usage, and regulations for quality and standardization for consumption. The PNE 2050 emphasizes the importance of addressing these challenges to create a favorable regulatory environment and attract investments (MME, 2020).

In comparison, in the United States, hydrogen has been considered an alternative fuel since 1992, with a regulatory framework that includes specific provisions to encourage its use, especially in electric vehicles. The Energy Policy Act of 1992 and regulatory activities of the U.S. Department of Energy have played a crucial role in this context (Campos, Leão, & Amorim, 2021). In the Brazilian context, there is discussion about the possibility of using the natural gas regulatory model for hydrogen injection into the network, with necessary adaptations to ensure the safety and proper operation of transportation and distribution networks (MME, 2020).

5.1.1. Regulatory Model of the Natural Gas Industry in Brazil

In the early 20th century, Brazil adopted an interventionist approach to the provision of essential services, leading to the creation of state-owned enterprises responsible for monopolizing the country's economic activities. However, the 1990s marked a significant change with the implementation of the National Privatization Program (PND), aimed at reorganizing the strategic presence of the state in the economy by transferring activities previously under public control to the private sector. The PND resulted in the transfer of controlling shares of state-owned enterprises to the private sector and the concession of public services previously carried out by the state.

In the natural gas sector, regulation in Brazil is outlined by the Federal Constitution, with the ANP regulating upstream and midstream activities up to the final delivery point (city gate). States, in turn, regulate downstream activities, including distribution, commercialization, and consumption. State regulation also covers the definition and revision of tariffs, as well as the regulation of free consumers, self-importers, and self-producers. State bodies, such as regulatory agencies or state secretariats, perform local regulatory and oversight functions for piped gas services, ranging from issuing mandatory standards to enforcing penalties for non-compliance with these standards and concession contracts (FGV, 2018; FGV, 2014).

5.1.2. The Role of Regulation in Hydrogen Injection into the Natural Gas Network

The development of the global hydrogen market, with zero or low CO_2 emissions, faces challenges such as the need for cost reduction through increased scale production, expansion of compatible infrastructure, and prioritization of production from renewable sources or fossil fuels with carbon capture, utilization, and storage technologies (CCUS), while hydrogen production technologies mature. The internationalization of hydrogen as a commodity is becoming increasingly plausible, requiring an adaptation of regulatory instruments to ensure technical standards, operational safety, and legal security of investments.

In the movement of the hydrogen-natural gas mixture, where there is no specific regulation at the moment, the comparative analysis uses the Brazilian regulatory framework for natural gas. Challenges, such as fragility in the network structure and risks associated with the flammability and compressibility of hydrogen, are identified. The central concern lies in the specific heat resulting from the mixture, affecting energy density and the need for adjustments in the measurement system or volumetric compensation methodology.

Regulation plays a crucial role in ensuring the quality of services and infrastructure, but its misapplication can negatively impact new investments. Standards and regulations are essential, providing technical requirements that ensure the safety of hydrogen activities. In the United States, the Department of Energy (DOE) leads research and development efforts, influencing national and international standards. In the European Union, strategies such as the Hydrogen Strategy and the "Fit for 55" package drive investments and integrate hydrogen into the energy sectors.

The European Union, with more than 220 hydrogen-related projects, seeks to create an internal market for this gas. The Hydrogen and Decarbonized Gas Markets package includes normative documents aimed at regulating hydrogen networks, establishing distinctions between rules for natural gases and other gases. These changes, significant for the pillars of the European Union, require adaptations from Member States, such as Germany and France, to align their hydrogen market projects with the new EU rules by 2031 (Chugunov & Kasyanov, 2022; Fleming, 2022; Zhou & Baldino, 2022).

5.1.3. Experience of Other Countries in the Regulation of Hydrogen Handling in Natural Gas Networks

In the regulatory landscape of the sociotechnical system of hydrogen, regulatory and certification frameworks encompass production, the supply chain, and elements of industrial use. The International Organization for Standardization (ISO) leads international standardization related to hydrogen systems, focusing on devices for production, storage, transport, measurement, and use of hydrogen. Currently, 17 public standards are under consideration, addressing technical factors, safety, separation and purification, storage, distribution, and final use, especially in the fuel cell vehicle transportation sector and refueling stations.

In the specific context of hydrogen transport by pipelines, tanker trucks, and its industrial use, globally recognized standards are not available and are specified by industry organizations such as the Compressed Gas Association (CGA) and the European Industrial Gases Association (EIGA). In Germany, legislation faced delays, leading to the adoption of unilateral measures and the establishment of legal frameworks on pure hydrogen networks before the European Union. The revision of the German Energy Industry Act in 2021 resulted in the implementation of a legislative framework addressing pure hydrogen networks, offering an “opt-in” regulatory choice to operators.

Operators opting for ‘opt-in’ have their hydrogen networks regulated, with specific legal and accounting requirements, including independence in the operations of hydrogen production, storage, and supply, separate accounting for hydrogen pipeline operations, and ensuring free network access for third parties under non-discriminatory conditions. The highly regulated energy market in Germany incorporates unbundling regulations, aiming to separate the operation of gas and electricity distribution and transportation networks from competitive activities of production, generation, and supply for end-use (Fleming et al., 2022; Hritsyshyna & Hutarevych, 2021; Ringsgwandl et al., 2022).

5.1.4. Start of the Brazilian and Cearense Regulatory Framework

In Brazil, the construction of the legal framework for the hydrogen sector began in 2021. Resolution CNPE No. 2/2021 from the National Council of Energy Policy included hydrogen as a theme to receive research and development resources in the energy sector (CNPE, 2021a). Resolutions CNPE No. 6 and No. 7, both from 2021, established studies for guidelines of the National Hydrogen Program

(PNH2), addressing issues such as energy transition and decarbonization. In July 2021, the Ministry of Mines and Energy (MME), in cooperation with other ministries, presented proposals for the PNH2, culminating in Resolution CNPE No. 6 of 2022, which instituted the program and defined its governance structure (CNPE, 2021b; CNPE, 2021c; MME, 2021b).

The State of Ceará, through the State Council for the Environment (COEMA), also contributed with Resolution COEMA No. 06 of 2022, which deals with environmental licensing of green hydrogen production ventures, considering potential polluting-degrading aspects and criteria such as electrolyzer power and H_2 production (CNPE, 2021d). The proposed guidelines for the PNH2 indicate the possibility of leveraging existing infrastructures, such as the natural gas pipeline network, for a competitive transition to a hydrogen economy.

In the legislative sphere, two bills (PL) in the Federal Senate seek to regulate hydrogen energy. PL No. 725/2022 addresses sustainable hydrogen and proposes injection targets into the network from 5% starting January 2032, while PL No. 1878/2022 focuses on green hydrogen. Both projects propose changes to Law 9.478/97, inserting competencies for the ANP to regulate the hydrogen chain, including production, import, export, storage, and use in the pipeline network.

Discussions on regulation in Brazil reveal a preference for ANP as the hydrogen regulatory agency, but issues related to certification of origin and purity are still unclear. The emergence of overlaps between ANP, National Electric Energy Agency and National Water and Basic Sanitation Agency, due to the production of inputs or energy in the hydrogen production process, highlights the need for a new regulatory body to cover the entire production chain. Regulatory discussions in Brazil are still in their early stages, and creating an attractive environment for private investments is crucial for the development of the hydrogen economy, requiring the appropriate use of regulatory instruments to ensure competition, production efficiency, and oversight of concession contract compliance. The regulation of hydrogen use in the natural gas infrastructure should be an integral part of governmental actions that favor the implementation and growth of the hydrogen economy, establishing clear and transparent rules. The current stage of planning and studying hydrogen regulation in Brazil may impact private investors' decisions to deploy businesses in the country or in other regions with more defined legal frameworks.

5.2. Final Considerations

The transition to carbon-free energy sources is crucial for combating the effects of greenhouse gases, with hydrogen emerging as a carbon-free energy carrier playing a significant role in global decarbonization. Despite being considered a promising option for global energy transition, hydrogen faces challenges, especially in the transportation and distribution stages. Pipeline transportation, despite being technologically advanced, requires significant investments for pipeline adaptations to meet the demands of hydrogen and natural gas mixture (Li et al., 2022).

The movement through pipelines in the hydrogen logistics chain is effective, efficient, and technologically mature, with low operational costs and long durability. However, the current extent of the hydrogen pipeline network is limited, representing a minimal fraction compared to the existing natural gas network. Mixing hydrogen into the natural gas network is considered a viable short-term alternative, allowing the gradual development of the industry without immediate investments in dedicated infrastructure.

Studies address challenges such as hydrogen-induced steel embrittlement, requiring further research to fully understand this phenomenon. Additives such as oxygen, acetylene, carbon monoxide, and nitrous oxide are explored to mitigate the effects of hydrogen on pipelines (Laureys et al., 2022; Martin et al., 2022). End-user acceptance is crucial, making the hydrogen and natural gas mixture an effective tool for an integrated climate-neutral energy system.

Regulation plays a crucial role in the successful deployment of the hydrogen industry in Brazil. The movement of hydrogen in the natural gas infrastructure requires a well-defined regulatory framework, including injection into the natural gas transportation and distribution network, gas quality, and commercial gas specifications. Recommendations from ACER and CEER include a gradual, dynamic, and cost-reflective regulatory approach to avoid cross-subsidies between gas and hydrogen network users (ACER, 2021).

The need for regulation is based on market failures, such as externalities, information asymmetry, and natural monopolies. In Brazil, the regulatory agency for the oil and gas sector may initially take on this role until the development of a specific body for the hydrogen chain. Existing regulatory instruments for the natural gas industry can guide the initial design of the regulatory model for the movement of the hydrogen and natural gas mixture.

6. Conclusion

The present study conducted a literature analysis to explore whether, for a zero or low-carbon energy transition, the injection of green hydrogen into the existing natural gas network would be feasible. The study identified perspectives and challenges associated with this action. After this comprehensive analysis and revisiting our initial questions, our study suggests the following answers:

1) ***Does Brazil and the State of Ceará have potential in renewable energy sources for the production of green hydrogen?***

Regarding the potential of renewable energy sources for green hydrogen production in Brazil and the State of Ceará, studies conducted by official agencies indicate the potential for: a) 117 GW for the installation capacity of offshore wind farms in shallow waters off the state's coast; b) 94 GW for onshore wind systems; and c) 137 GW for hybrid systems (solar and wind) (Associados, 2019). Ceará currently has an installed generation capacity of over 5 GW, with a forecasted addition of approximately 8 GW in the coming years (ANEEL, 2023).

As evident, Brazil, and specifically the State of Ceará, are aligned with the new era of green energy and have a strong potential to meet the demands of the green hydrogen industry through solar and wind energy sources. This scenario favors the pipeline transport of the hydrogen-natural gas mixture to decarbonize end-use sectors, including domestic, commercial, and transportation sectors, and has been suggested as a first step in transitioning to a hydrogen economy.

2) ***What are the challenges in utilizing natural gas infrastructure for green hydrogen transportation?***

The literature analysis reveals that it is feasible to adapt or convert the natural gas infrastructure to transport hydrogen-gas mixtures, provided that impactful factors are considered. These factors include the effects of hydrogen on the pipeline structure, the influence of concentration on temperature, pressure, and compressibility, as well as the necessary changes to system components and facilities. Specific challenges are such as monitoring calorific value, measurement equipment, and equipment modifications, deserve special attention. However, the exposure of pipelines to the aggressive hydrogen environment, leading to hydrogen embrittlement, represents a significant challenge for using steel pipes in hydrogen transportation.

Despite these challenges, the literature indicates that the gas network has the potential to play a crucial role in the energy transition to a low or zero-carbon system. The existing infrastructure can be initially used for transporting methane-hydrogen blends, followed by operational modifications and a gradual increase in hydrogen concentration in the mixtures. However, it is essential to conduct exhaustive research and experiments to ensure the maturity and reliability of network conversion technologies, considering changes to pipelines, equipment, and the precise definition of hydrogen concentration in the mixture (Mahajan et al., 2022).

3) ***Who has regulatory competence in Brazil for injecting green hydrogen into the natural gas network?***

Regarding the regulatory aspects of green hydrogen transportation and distribution in Brazil through the natural gas network, it is evident that the definition of the activity's competence is still in the early stages, with many discussions and limited effectiveness. Stakeholders, including governments, investors, regulatory institutions, and academics, align on certain aspects while differing on others, particularly concerning the division of responsibilities among existing regulatory agencies. This includes potential amendments to their founding laws, as seen in the cases of PL 725/2022 and PL 1878/2022, or the creation of a new specific regulatory body for hydrogen, encompassing either the entire hydrogen chain or parts of it.

In this context, an appropriate and transparent regulatory framework with well-defined rules is crucial as one of the pillars to attract investments for the development of the green hydrogen market in Brazil. Regulating economic activities (Upstream and Midstream) or the provision of public services (Downstream) through regulatory agencies with autonomy and adherence to the best technical and legal practices signals regulatory maturity and legal security to private investors. Therefore, it is suggested that the regulation and oversight of the hydrogen and natural gas mixture transportation activity be carried out through an existing regulatory agency until the establishment of a specific regulatory entity covering the hydrogen industry.

4) ***Can the regulation of the natural gas industry in Brazil be used as an initial basis for regulating green hydrogen?***

Concerning the question of whether the current regulation of the natural gas industry can serve as a basis for regulating the movement of green hydrogen and natural gas, it is important to note that the Brazilian regulatory model for natural gas involves two federal entities: the Union, responsible for regulating the economic activities of production, processing, storage, and transportation of natural gas; and the states, with the authority to regulate distribution activities supplying gas to end-users within their geographical limits.

In the case of hydrogen and natural gas, both sectors characterized by long-term contracts, high implementation costs, and specific assets, the decision of private investors depends on their confidence in the State's ability to fulfill future commitments made in the present. An initial assessment of gas pipeline regulation for hydrogen in the European Union (Fleming, 2022) suggests that a model similar to the current regulation of natural gas could be developed.

However, this cannot be done instantly, as technical and operational aspects must be considered. The current regulation was designed for natural gas, and there are some differences in the Upstream, Midstream, and Downstream stages compared to hydrogen. The adoption of efficient public policies is crucial to foster the new hydrogen economy and its supply chain. At this point, it is not only the interest of the industry and investors but also the harmonization of tax, environmental, and social policies. Legal security and good sectoral governance practices are essential to support this activity, contributing to the energy transition.

Thus, considering the existence of a consolidated regulatory model for gas and the absence, up to the present moment, of normative instruments for this activity, our study suggests adopting, as an initial basis for formulating a regulatory policy, the parameters of the Brazilian regulation of the natural gas industry until the creation of a specific regulatory entity for the hydrogen industry and the definition of its regulatory framework covering the entire production chain.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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