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Article

Hydrogen in the Energy Transition: Challenges and Solutions for Environmental Safety in the Northern Region of Rio de Janeiro

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ABSTRACT

The energy transition toward a low-carbon economy has driven global interest in technologies associated with hydrogen as a clean and versatile energy carrier. In this context, this article aims to conduct an exploratory bibliometric analysis based on a systematic review of the scientific literature and an analysis of existing projects, evaluating the feasibility of implementing this new energy matrix in the Northern Fluminense region. Projects on a national and international scale were analyzed, including initiatives such as the *European Hydrogen Backbone*, the H2Med corridor, hydrogen *hubs* in Australia and Asia, as well as Petrobras projects in the Port of Açu and in states such as Bahia and Piauí. The research adopts a multidisciplinary approach, addressing technical, environmental, regulatory, and socioeconomic aspects, with an emphasis on territorial feasibility and the risks associated with hydrogen embrittlement, a phenomenon that compromises the integrity of materials exposed to this element. The study highlights the most promising technological alternatives, such as geological storage in salt caverns and the use of materials resistant to hydrogen degradation, in addition to addressing the need for regulatory updates, integrated environmental planning, and occupational safety protocols. The results indicate that, despite structural and environmental challenges, the region has strategic potential to integrate into the hydrogen value chain, provided it is supported by coherent public policies, technical rigor, and social participation.
Keywords: hydrogen; storage; transportation; environmental risks; Northern Rio de Janeiro.

RESUMO

A transição energética rumo a uma economia de baixo carbono tem impulsionado o interesse global por tecnologias associadas ao hidrogênio como vetor energético limpo e versátil. Nesse contexto, o presente artigo tem como objetivo uma análise bibliométrica de caráter exploratório, baseada na revisão sistemática da literatura científica e na análise de projetos existentes, avaliando a viabilidade da implementação dessa nova matriz energética na região Norte Fluminense. Foram analisados projetos em escala nacional e internacional, incluindo iniciativas como o *European Hydrogen Backbone*, o corredor H2Med, *hubs* de hidrogênio na Austrália e na Ásia, bem como projetos da Petrobrás, no Porto do Açu e em estados como Bahia e Piauí. A pesquisa adota uma abordagem multidisciplinar, contemplando aspectos técnicos, ambientais, normativos e socioeconômicos, com ênfase na viabilidade territorial e nos riscos associados à fragilização por hidrogênio, fenômeno que compromete a integridade de materiais expostos a esse elemento. O estudo destaca as alternativas tecnológicas mais promissoras, como o armazenamento geológico em cavernas de sal e a utilização de materiais resistentes à degradação por hidrogênio, além de abordar a necessidade de atualização regulatória,

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planejamento ambiental integrado e protocolos de segurança ocupacional. Os resultados apontam que, apesar dos desafios estruturais e ambientais, a região apresenta potencial estratégico para integrar a cadeia do hidrogênio, desde que amparada por políticas públicas coerentes, rigor técnico e participação social.

Palavras-chave: hidrogênio; armazenamento; transporte; riscos ambientais; Norte Fluminense.

Introduction

Since its discovery in 1766 (RSC, [n.d.]), hydrogen has been studied as an energy carrier, gaining relevance in the context of the energy transition. With advances in scientific research and growing interest in alternative energy sources, hydrogen has come to be considered one of the most promising energy carriers in the context of the global energy transition, due to its decarbonization potential and versatility of application. As presented in the report prepared by McKinsey & Company (2024), there has been significant growth in the number of projects focused on hydrogen development in recent years.

Given the significant increase in projects focused on large-scale hydrogen production and distribution, technological advancements and their impact on scientific output have become particularly relevant. In this context, a bibliometric survey was conducted to analyze the temporal evolution of publications on hydrogen, as well as to identify trends and gaps in scientific output, with a focus on production, transportation, and storage processes and the associated environmental impacts.

Although it holds great potential, hydrogen still presents significant challenges, especially regarding the safety of its transport and storage chains. As an extremely volatile and flammable gas, its handling requires specific technologies and rigorous protocols. As noted by Li et al. (2022), in the presence of oxygen, any crack or leak in pipelines and pressurized containers can cause explosions, posing significant risks to both the environment and nearby populations. In this sense, analyzing the risks associated with transportation and storage is essential for the safe planning of the hydrogen supply chain. On the other hand, from a technical standpoint, one of the advantages of hydrogen as an energy carrier is its high energy density, with 1 kg of hydrogen containing about 2.4 times more energy than natural gas (CSIRO, 2022).

From a theoretical perspective, this research is grounded in approaches related to the energy transition, energy system security, and the analysis of socio-environmental risks. The analytical framework is based on understanding hydrogen as an energy carrier within a system in which technological, environmental, and territorial aspects are interrelated. In addition, concepts such as *hydrogen embrittlement*, energy infrastructure safety, and territorial planning are employed, guiding the analysis and interpretation of data, as well as the identification of the main gaps and challenges associated with the implementation of this chain in the Northern Rio de Janeiro region.

For data collection, the CAPES Journal Platform was used, employing integrated search tools that bring together national and international indexed databases. The research was conducted in September 2025, covering the years 2010 to 2024, in order to encompass the most recent period of expansion in publications relevant to the topic. Figure 01 presents the total number of articles published between 2010 and 2024, highlighting the growth trend over the years regarding the topic and demonstrating the increasing academic and technological interest in the consolidation of hydrogen as an energy vector. It should be noted that the figures presented do not correspond to distinct, unique publications, as a single article may be indexed under multiple keywords, resulting in overlap among the analyzed categories.

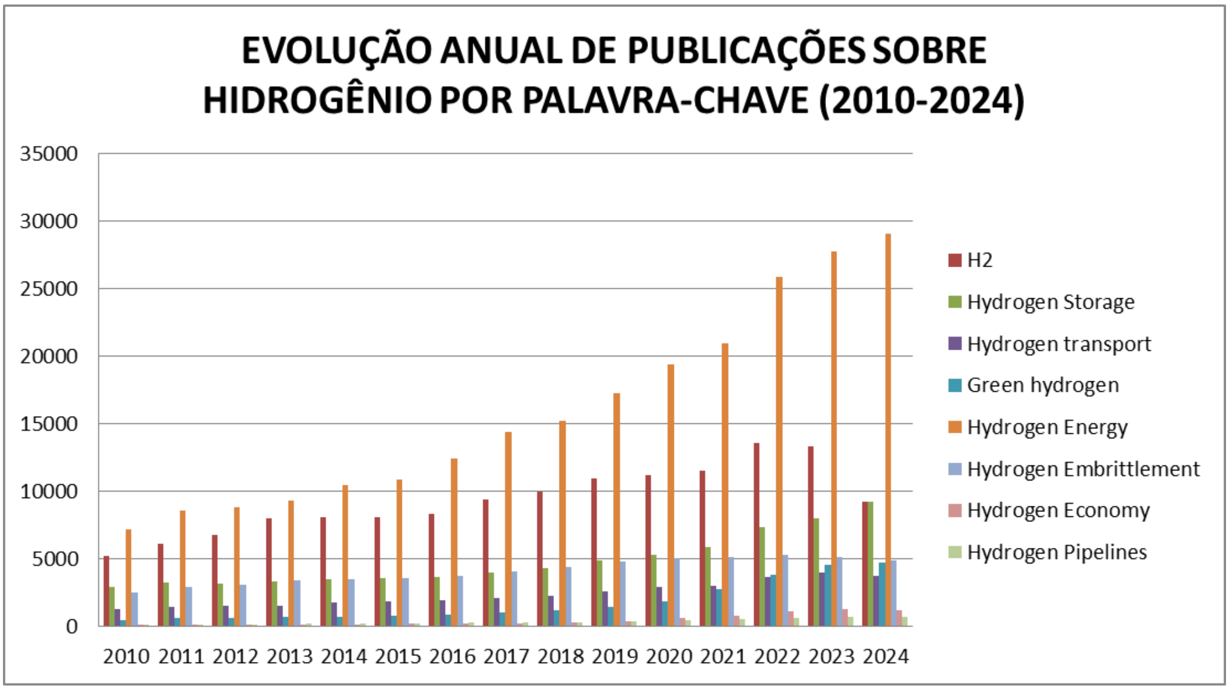

Figure 01: Annual evolution of publications on hydrogen by keyword between 2010 and 2024. Source: Author's own work, based on data obtained from the CAPES Journal Platform.

Figure 02 shows the distribution of published articles according to keywords associated with the topic of hydrogen on the CAPES Journal Platform between 2010 and 2024, based on a survey conducted in November 2025. It can be observed that the term *"Hydrogen energy"* accounts for nearly half of the occurrences (41%), followed by "H_2" (24%). The remaining keywords—*"hydrogen storage," "hydrogen transport," "green energy," "hydrogen economy*," *"hydrogen embrittlement*," and *"hydrogen pipelines*"—account for the remaining 35%. These results indicate that, although research still prioritizes general approaches to hydrogen, more specific topics, such as hydrogen embrittlement, transport infrastructure, and storage, have been gaining relevance in recent years. It is worth noting that the figures presented do not correspond to distinct studies, since a single article may be indexed under multiple keywords, leading to overlap between categories. Despite this limitation, the data highlight hydrogen as an energy vector in the international scientific landscape, as well as the gradual expansion of discussions regarding its associated infrastructure.

The analysis allowed us to identify the thematic interconnection among the subfields of hydrogen-related research, demonstrating the interdisciplinary nature of the topic. Using this methodology, we observed the progressive growth of the academic field in publications over the past 15 years, as well as significant growth beginning in 2020.

This growing attention from the scientific community reflects the strategic importance of hydrogen in the global energy mix. In this context, according to the 2019 *International Energy Agency* (IEA) Report, for a total production of 70 million metric tons (Mt) of hydrogen per year, approximately 205 million m^3 of natural gas, which is approximately 6% of the total natural gas consumed by the population over the course of a year (IEA, 2019).

In 2023, global hydrogen demand reached 97 Mt, representing a 2.5% increase over the previous year. It is estimated that by 2030, the supply capacity of low-emission hydrogen, such as water electrolysis and production from fossil fuels with carbon capture (CCUS), will reach 49 Mt/year based on ongoing projects, which is nearly 30% more than projected in *the International Energy Agency's* 2023 Report (IEA, 2024).

Global hydrogen demand increased by about 2% in 2024 compared to the previous year, reaching approximately 100 Mt, with consumption concentrated primarily in the oil refining and industrial sectors. In contrast, low-emission hydrogen production grew by 10% over the same period; however, it accounts for only 1% of the global total. Projects already in operation or that have reached the final investment decision (FID) are projected to reach 4.2 Mt per year by 2030, corresponding to an increase of approximately five times compared to 2024 levels (IEA, 2025).

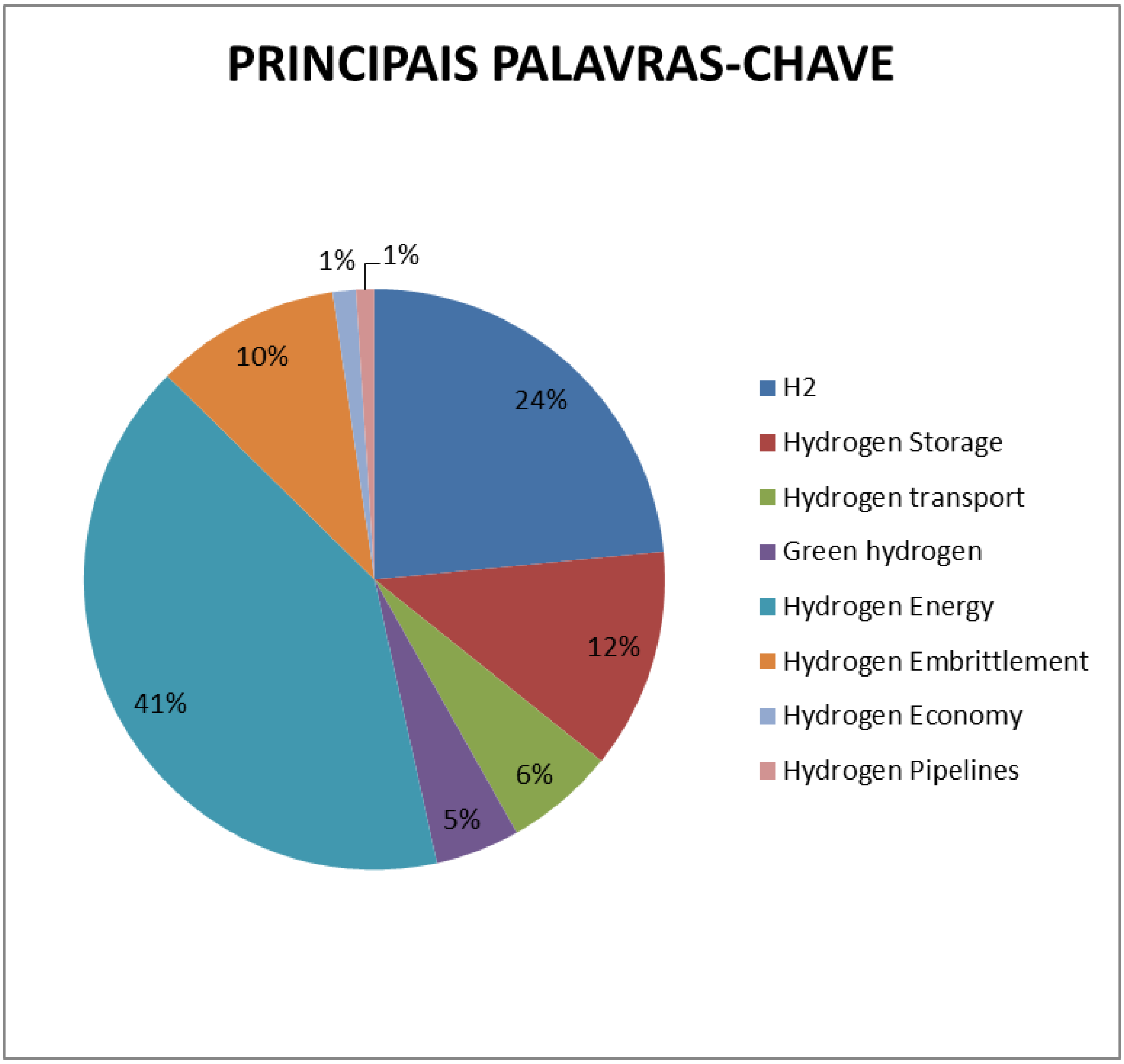

Figure 02: Main search keywords. Source: Author's own work, based on data obtained from the CAPES Journal Platform.

From an energy perspective, hydrogen has a high energy density, with a value of 120.1 megajoules per kilogram (MJ/kg), which is nearly three times the energy density of gasoline. This advantage is one of the main factors justifying the interest in hydrogen as a long-term energy carrier (IEA, 2019).

This study aims to assess the feasibility of implementing a hydrogen supply chain in the Northern Rio de Janeiro region through an exploratory bibliometric analysis based on a systematic review of the scientific literature and an analysis of national and international projects, taking into account technical, environmental, regulatory, and socioeconomic aspects. Additionally, it analyzes the challenges related to the implementation of hydrogen transport and storage infrastructure, with an emphasis on the types of materials used in piping, as well as the different forms of gas storage.

Materials and Methods

Material

The sources used to prepare this article included published theses, documents, books, and case studies related to the topic, as well as government *websites* and companies focused on the implementation of hydrogen as an energy source and fuel.

Method

The research was exploratory-descriptive in nature, focusing on contextualizing, substantiating, and surveying scientific articles on this topic, with the aim of identifying the potential impacts and contamination that could occur with hydrogen transport and storage facilities, focusing on impacts on fauna and flora, as well as safety regarding leaks and socioeconomic impacts generated in the Northern Rio de Janeiro region.

For the literature review, the CAPES Journal Portal database was primarily used. The selection of articles focused on the following thematic areas: green hydrogen, socio-environmental impacts, pipelines and transportation, pipeline embrittlement, and economics. The keywords used in the searches included: *"hydrogen energy*," "socioeconomic," *"hydrogen embrittlement*," and *"hydrogen pipelines*," chosen for their relevance and ability to capture the most significant literature related to the topic. We chose to use English terminology in order to broaden the scope of the research and enable the identification of a more significant number of articles relevant to the subject.

The selection of articles used in the research was initially conducted by analyzing the titles to identify those directly aligned with the topic. This was followed by a second screening stage, based on reading the abstracts, to confirm the relevance and alignment of the content with the study's central questions.

Although a formal systematic protocol, such as PRISMA, was not adopted, the review, being exploratory in nature, aimed to map the technological and regulatory development of low-carbon hydrogen. For this reason, no quantitative criteria were applied to count identified, included, or excluded studies, as the central objective of the research was to identify themes, convergences, gaps, and concepts essential to constructing the theoretical framework of the research.

The inclusion of works followed qualitative criteria based on: adherence to the thematic axes; scientific or institutional relevance of the sources; and timeliness of the content, giving priority to the most recent materials. Exclusion occurred when the materials had a tangential focus, a theme distant from the scope, or a lack of information applicable to the research objective.

In addition to publications indexed in the CAPES Journal Platform, other complementary data sources were also consulted to enrich the analysis with up-to-date and contextualized information. Among these sources, institutional documents stand out, such as technical reports and investment plans for sustainable technologies. Companies and projects relevant to the development of green hydrogen in Brazil were also included in the analysis, such as the Port of Açu located in the Northern Rio de Janeiro region; reports from *McKinsey & Company* and the International Energy Agency (IEA) also added value to the study.

The diversity of sources aimed to ensure a comprehensive and multidisciplinary approach, capable of connecting academic knowledge with practices in the productive sector, thereby contributing to a more complete view of the potential and implications of hydrogen in the Brazilian context.

Literature Review

Brazil occupies a prominent position in the global energy landscape, ranking among the countries with the highest installed renewable energy capacity (IRENA, 2023). According to projections by McKinsey & Company (2024), the country could achieve, by 2030, a production cost for green hydrogen of around US$1.50 per kilogram. This figure is close to estimates for leading nations in the sector, such as Australia, the United States, Saudi Arabia, and Spain, which are expected to reach around US$1.25/kg by 2040 (MME, 2024).

In 2023, hydrogen production emitted approximately 920 Mt of CO_2, predominantly from processes without emissions mitigation (IEA 2024). The predominant route remains *Steam Methane Reforming* (SMR), accounting for about two-thirds of global production, with emissions ranging from 10 to 12 kg of CO_2equivalent per kilogram of hydrogen. Considering all fossil-based technologies, it is estimated that 96% of global hydrogen still comes from non-renewable sources (IEA, 2023). In contrast, electrolysis accounted for only 2% of production in 2021, with projections to reach approximately 34% by 2030, driven by the expansion of electrolysers and decarbonization policies. Mitigation costs range from $60 to $85/t of $CO_2$for capture rates of 55–70%, and can reach $85 to $110/t of $CO_2$for rates above 90% (IEA, 2024). According to the IEA report (2024), 75% to 95% of these emissions occur at the point of production, and emissions can be reduced through carbon capture.

Hydrogen produced through water electrolysis has virtually zero emissions at the point of production; however, its environmental viability depends on the carbon intensity of the electricity used in the process. The electricity used must have an intensity of less than 200–240 g CO_2/kWh (IEA, 2024).

However, according to data from the Hydrogen Council, investments committed for 2025 already exceed US$110 billion, with more than 500 projects currently in the final investment decision (FID) phase, under construction, or already operational. This represents an increase of US$35 billion compared to the previous year (2024). Among global projects, China leads in investments, with approximately US$33 billion in renewable hydrogen production, followed by North America with US$23 billion and Europe with US$19 billion (HYDROGEN COUNCIL, 2025).

According to the *Hydrogen Scaling Up* Report (HYDROGEN COUNCIL, 2017), the first consolidated estimates of hydrogen's economic potential at the global level indicate a market size of around US$2.5 trillion per year by 2050, considering sales of hydrogen and associated equipment. This projection reinforces the reduction of $CO_2$by up to 6 Gt annually and the creation of more than 30 million jobs.

Currently, natural gas ranks among the primary feedstocks for hydrogen production via the steam reforming process. However, despite its relevance and technical feasibility, this route has significant limitations, primarily due to the substantial associated carbon emissions, which underscores the need to accelerate the transition to cleaner and more sustainable alternatives (SHARMA et al., 2023).

International and National Overview of Hydrogen Infrastructure.

In recent years, several countries have made progress in developing large-scale hydrogen transportation and storage networks, seeking to facilitate the transition to the hydrogen market and, in doing so, decarbonize their energy mixes. In Europe, the *European Hydrogen Backbone* (EHB) Project stands as one of the leading examples, bringing together initiatives from 28 countries focused on adapting existing gas pipelines, as well as constructing dedicated pipelines and implementing new underground storage systems in salt caverns and depleted reservoirs. This strategy demonstrates a trend toward leveraging existing infrastructure, reducing costs and impacts associated with the construction of new pipelines (EHB, 2024; IEA, 2023).

According to the IEA's *Net Zero Emission by 2050* (NZE) scenario (2024), with increased production through electrolysis powered by renewable sources, the cost of hydrogen production is expected to fall to $2–9 per kilogram of hydrogen—half the current cost—while the cost of hydrogen produced from fossil fuels will decrease substantially, dropping from $1.5–8 per kilogram to $1–3 per kilogram by 2030.

According to the IEA report (2024), approximately $50 billion per year would be needed over the next decade to enable the expansion of projects to align with the NZE scenario.

In this context, the European experience serves as an important reference point for reflecting on the Brazilian case. The hydrogen network in Europe is being planned by the *European Hydrogen Backbone* (EHB) initiative, which provides a country-by-country overview of national strategies for the energy transition. The EHB portal features descriptions of existing infrastructure, pipeline adaptation projects, plans for constructing new hydrogen-dedicated routes, as well as timelines with projected start and/or completion dates (EUROPEAN HYDROGEN BACKBONE, 2024). Following this general overview, the table below highlights the main European projects.

Table 01: Overview of national strategies for hydrogen infrastructure within the European Hydrogen Backbone (EHB).

COUNTRY	SCOPE	MODES OF TRANSPORT	EXPECTED COMPLETION
AUSTRIA	1,700 km	Transported mixed with methane or in pure form Two-way transport, integrating existing pipelines	By 2035, it would be ready to function as a full-fledged hub
BELGIUM	4,000 km of gas pipelines with interconnections	Plans to reconfigure its natural gas pipeline networks for H_2 transport, importing and exporting the gas	First hydrogen infrastructure expected to be ready in 2026
BULGARIA	3,380 km of high-pressure gas pipelines and underground storage facilities	A nationwide hydrogen transmission infrastructure is under development, with gas and oil pipelines already ready for H_2 use. Plans are in place to retrofit the pipelines to transport H_2in concentrations of up to 10%	No exact date set
CROATIA	2,500 km of transmission and distribution pipelines	Reuse of existing interconnections and construction of new pipelines	Retrofitting by 2040, followed by infrastructure expansion
CZECH REPUBLIC	4,000 km of gas pipelines with interconnections	Retrofitting of existing gas pipelines for hydrogen transport	Cross-border transport by 2030 and expansion of infrastructure by 2040

DENMARK	925 km of gas pipelines, expanding to 1,250 km	Reuse of existing pipelines and construction of new pipelines, connecting branch lines to offshore H_2 production	Infrastructure by 2030, with a capacity of 6.5 GW. Full interconnections by 2040
ESTONIA	977 km of gas pipelines plus an undersea interconnector with Finland	Construction of new pipelines due to the lack of parallel natural gas pipelines	Initial development in 2030 and subsequent expansion over the years
FINLAND	1,300 km of gas pipelines and an undersea interconnector with Estonia	Construction of new pipelines, subsea interconnectors, and connections to the Nordic and Baltic corridors	Regional connections by 2030 and a national network by 2040
FRANCE	Over 37,000 km of gas pipelines	Transported mixed with other gases; construction of dedicated H_2 pipelines and offshore interconnections	Regional hubs by 2030 and a consolidated and mature infrastructure by 2040
GERMANY	12,000 km	Reuse of gas pipelines, construction of new pipelines and interconnections	Initial national network between 2027 and 2032
GREAT BRITAIN	7,630 km	Reuse of gas pipelines, new construction of sections where necessary	By 2035, connection of industrial clusters; between 2035 and 2040, adaptation of existing gas pipelines
GREECE	1,456 km	New hydrogen pipelines, following the existing route	By 2030, connection of the main clusters; interconnection with adjacent systems by 2040
HUNGARY	5,874 km of existing gas pipelines	Construction of new dedicated pipelines and repurposing of certain sections	By 2030, a north-south corridor could be built; by 2040, a mature network with interconnections
IRELAND	2,477 km of transmission pipelines and 12,044 km of distribution pipelines	Reuse of gas pipelines, construction of new pipelines, and subsea interconnections	Hydrogen "village" network by 2035 and an interconnector converted to transport 100% hydrogen by 2040
ITALY	Over 32,500 km of	Repurposing and construction of	National backbone network by

	transmission network	dedicated hydrogen pipelines, imports via North Africa	2030, expansion and interconnections by 2040
LATVIA	1,190 km of gas pipelines	Partial repurposing of existing pipelines and the creation of dedicated hydrogen pipelines, mixed transport with other gases	Technical study by 2024, with results to inform future decisions
LITHUANIA	2,285 km of high-pressure gas pipelines	Blending, adaptation of gas pipelines, and new dedicated H_2 pipelines	Hydrogen infrastructure starting in 2030, regional connectivity to follow
LUXEMBOURG	2,175 km with interconnections	Reuse of interconnections and construction of new pipelines if necessary	Full connection of the main network is planned by 2040
NETHERLANDS	16,000 km of gas pipelines	Reuse of existing natural gas infrastructure and construction of new offshore pipelines	Main network expected to be operational by 2027, with network expansion by 2030
NORWAY	9,000 km of mixed gas pipelines, both onshore and subsea	Hydrogen blending in transportation, repurposing of export gas pipelines, and planning for new pipelines	Modification of pipelines by 2030 and new connections by 2040
PORTUGAL	5,493 km of distribution pipelines	Transportation blended with natural gas (up to 15% hydrogen in the blend) and construction of dedicated pipelines	Expansion to a 100% hydrogen network between 2035 and 2040
ROMANIA	Not reported	Repurposing of gas pipelines and construction of new sections to connect regional corridors	Development aligned with European corridors from 2030 to 2040
SLOVAKIA	Not reported	Reuse of gas pipelines, connection to import routes and national hubs	Initial flows and possible inflows as early as 2030, consolidation by 2040
SLOVENIA	1,195 km for domestic gas transport	Reuse and regional interconnections	Integration with the main regional network between 2030 and 2035,

			completion in 2040
SPAIN	Gas network spanning 11,000 km	Reuse of pipelines, construction of new pipelines, imports via ports, and integration with North Africa	Development of corridors by 2030 and 2035; expansion by 2040
SWEDEN	Length not specified; network focused on connections to the Nordic market	Reuse of existing pipelines, new regional pipelines, and connections to the Baltic/Nordic corridors	Implementation between 2030 and 2040
SWITZERLAND	Not specified	Reuse of cross-border interconnections	Integration into the main European grid planned by 2040
UKRAINE	Not reported	Not reported	Not reported

Source: Author's own work, data extracted from EUROPEAN HYDROGEN BACKBONE (2025).

The table above provides an overview of the 28 countries participating in *the European Hydrogen Backbone*, explaining how each country plans its hydrogen transport infrastructure. In many cases, the strategy adopted involves retrofitting existing infrastructure to transport hydrogen by blending it with natural gas, as well as constructing new dedicated pipelines where necessary. The estimated timeline across all participating countries ranges from 2030 to 2040, with a gradual and phased rollout.

Still within the European context, the H2Med project stands out as one of the main transnational hydrogen infrastructure projects, connecting the Iberian Peninsula to Northwestern Europe. Its timeline calls for studies to be conducted between 2022 and 2027, followed by the implementation phase between 2027 and 2029, with an estimated budget of €2.5 billion. Operations are projected to begin in 2032, with a transport capacity of approximately 2 million tons of hydrogen per year (H2MED, 2025). Additionally, the $\mathrm{SouthH_2}$ Corridor stands out, an infrastructure dedicated to hydrogen transport consisting of approximately 3,300 km of pipelines connecting North Africa to Italy, Austria, and Germany. The project is expected to come on y operation in 2030, with the potential to import around 4 million tons of hydrogen annually, capable of meeting up to 40% of the target set by the REPowerEU program.

Beyond Europe, other regions of the world are consolidating strategic investments in hydrogen technologies, particularly in the Asia-Pacific region. In Japan, the Fukushima Hydrogen Energy Research Center—already in operation—stands out, with the goal of producing low-cost green hydrogen from renewable sources. The plant has a generation capacity of approximately 1,200 Nm^3 of hydrogen per hour using solar energy, making it one of the largest green hydrogen facilities in the world (NEDO, 2020).

Also in the region, Australia and Japan have developed a joint pilot project launched in 2018, focused on producing hydrogen from brown coal through gasification and gas refining processes. The hydrogen produced is subsequently liquefied and transported by ship to the port of Kobe, Japan. The first shipment took place in January 2022, and the project is expected to reach commercial scale around 2030 (DCCEEW, 2022).

Complementing this, KOGAS (Korea Gas Corporation) is spearheading an initiative to expand hydrogen infrastructure in the city of Gwangju, South Korea. The project involves the production of zero-carbon green hydrogen, with a goal of reaching a cost of 6,000 KRW (Korean Won) per kilogram (approximately R$22, as of December 2025) by 2030. Projections indicate a production capacity of 100,000 tons per year in 2025, expanding to 1 million tons per year by 2030 (KOGAS, [n.d.]).

In addition, South Korea's sustainable mobility sector has been driven by initiatives from the Hyundai Motor Group, which, in partnership with the city of Pyeongtaek, is developing a national model for port decarbonization. The plan includes the installation of hydrogen fuel cell power generators at the port, with the aim of creating infrastructure for large-scale transportation. A pilot project was carried out in November 2024, and in November 2025, a memorandum of understanding was signed to expand the model, utilizing approximately 15 km of existing infrastructure (HYUNDAI, 2025).

In a similar context, the Australian government has played an active role in consolidating the low-carbon hydrogen supply chain through public investments aimed at developing regional hydrogen hubs. It is estimated that approximately US$500 million is being allocated to the implementation of *hydrogen hubs*, with a focus on engineering studies, project design, and technological improvement, aiming to integrate hydrogen production, storage, transportation, and final consumption (AUSTRALIAN GOVERNMENT, 2025).

In this regard, a major integrated project for renewable energy generation and hydrogen production in Western Australia stands out, combining wind and solar power plants with a total capacity of 6 GW, intended to power 3 GW of electrolysers. The project is expected to produce up to 1.9 million tons of green ammonia per year, with a focus on exports to Japan and South Korea by 2030. Construction is scheduled to begin in 2027, with a Final Investment Decision (FID) estimated for late 2026, totaling an investment of approximately A$814 million, funded by the *Australian Hydrogen Headstart* program (AUSTRALIAN TRADE AND INVESTMENT COMMISSION, 2024).

Another strategic project is the *Port Bonython Hydrogen Hub,* located in the state of South Australia, which brings together government and private investments and is valued at up to US$13 billion. The hub has a projected capacity to produce approximately 1.8 million tons of hydrogen by 2030, in addition to contributing significantly to regional economic development. Projections indicate the creation of more than 16, ,000 jobs by 2050, with an estimated impact of US$50 billion on Australia's Gross Domestic Product (GDP) (AUSTRALIAN GOVERNMENT, 2023).

Additionally, the Australian government supports smaller-scale, demonstration-based initiatives, such as *Hydrogen Park South Australia* (HyP SA), which has received approximately A$14.5 million in investment and operates 1.25 MW electrolysers for the local use of renewable hydrogen. Added to this portfolio is the *Eyre Peninsula Gateway* project, developed by *Hydrogen Utility* (H2U), which plans to install 75 MW of electrolysers for the production of green hydrogen and ammonia, reinforcing Australia's strategy of technological diversification and strengthening the hydrogen production chain (GOVERNMENT OF SOUTH AUSTRALIA, 2025).

Applying this overview to the Brazilian context allows for a comparison of European models with the national reality, identifying strategies that prove more compatible, such as the adaptation of existing infrastructure or the establishment of import corridors. In this regard, the Northern Rio de Janeiro region emerges as a strategic territory, given its consolidated infrastructure in the oil and gas sector, which facilitates the adaptation of existing pipelines.

In addition to European initiatives, Brazil has also been investing in projects focused on the production, transportation, and storage of hydrogen, reflecting a movement toward alignment with international trends.

To contextualize the importance of the national landscape in the development of the hydrogen economy, Table 02 presents a survey of national projects focused on hydrogen production. It highlights data such as production, capacity, investment, and the current stage of the project, demonstrating that the country has structured its participation in the energy transition and the integration of renewable energy

Table 02: National projects focused on hydrogen production

NATIONAL PROJECTS	**PRODUCTION AND CAPACITY**	**INVESTMENT**	**PROGRESS**	**LOCATION**
Fortescue: Pecém Green Hydrogen Project	Production: 500 tons of hydrogen via electrolysis	R$ 20 Billion	Project in the feasibility phase, but the Preliminary License (LP) has already been granted	Ceará
Green Energy Park	Production: 2.4 million tons of green hydrogen Capacity: 10.8 GW	R$ 200 billion	The project began in 2023, with construction expected to start in 2028	Piauí
Solatio	Production: 4 GW of hydrogen and s of ammonia as an energy carrier (via green H_2) Capacity: 11.4 GW	R$ 25 billion in projects across Brazil	Construction to begin in 2025	Piauí
Project carried out at the Port of Açu in collaboration between Prumo Logística, the Port of Açu, and Fuella AS	Production: 400,000 tons of green ammonia as an energy carrier (via green H_2) per year Capacity: 520 MW	Not yet announced	The final decision is expected in the coming years, and the first molecules will be delivered by 2030	Rio de Janeiro
Unigel	Production: 100,000 tons of green hydrogen and	$1.5 billion	The first phase of the project is already under construction	Bahia

	600,000 tons of ammonia as an energy carrier (via green H_2) per year Capacity: 60 MW		with an initial investment of US$ 120 million	
Casa dos Ventos and Comerc project in Pecém	Production: 4,000 tons per day Capacity: 2.4 GW	$4 billion	The first phase is scheduled for 2026	Ceará
AES Brasil	Production: 800,000 tons of green ammonia as an energy carrier (via green H_2) per year Capacity: 2.5 GW	$2 billion	Undisclosed	Ceará

Source: Adapted from Fortescue Brasil (2025); GEP-Piauí (2025); Brazil (2025); Brazilian Industrial Hub (2024); Bahia (2023); Pecém Complex (2022); Ceará (2022).

Although most projects are still in the early stages, there is a concentration in strategic locations such as port areas and industrial hubs like Pecém (CE), Suape (PE), and the Port of Açu (RJ). This configuration highlights Brazil's potential to integrate logistics networks for hydrogen export and distribution, demonstrating compatibility with the *European Hydrogen Backbone* (EHB) model.

In addition to these projects, Petrobras has been investing in natural hydrogen research, with an initial capital of R$20 million, set to begin in 2023 in Bahia with plans to expand to other states (PETROBRAS, 2024). Petrobras also plans to operate its first pilot plant for renewable hydrogen production, scheduled to be operational in 2026. With an investment of R$90 million, the plant will be built at the Vale do Açu Thermal Power Plant in Rio Grande do Norte. The process for producing green hydrogen will involve electrolysis using solar energy, with a capacity of 2 MW. The energy produced will be used in studies on the addition of hydrogen to natural gas to power microturbines (PETROBRAS, 2024).

Gonçalves et al. (2025) emphasize that, although Brazil possesses competitive advantages such as a renewable energy matrix, challenges involving legislation and technological innovation still need to be further studied and improved in order to attract investments. Social aspects such as public acceptance and potential socio-environmental impacts must also be taken into account, as they are of fundamental importance for the project's implementation in the region and require the community's understanding of the risks and benefits of this new technology (ALMARAZ et al., 2024).

Comparing international models with ongoing projects in Brazil reveals that both seek solutions that balance operational safety, economic viability, and environmental sustainability. Despite the progress, when comparing national and international advancements, European countries already have more advanced projects in more consolidated stages of regional integration and infrastructure adaptation for hydrogen transport, whereas Brazil is still in the initial phase of structuring both the regulatory framework and technological consolidation. Thus, it can be observed that both seek to utilize existing gas pipeline infrastructure, particularly natural gas networks, as a way to minimize the costs of constructing new pipelines and to mitigate the socio-environmental impacts that would otherwise be generated.

Potential configurations for hydrogen transport and storage in the Northern Rio de Janeiro Region.

Based on the international and national overviews presented, it is possible to draw parallels with the energy context of the Northern Rio de Janeiro region, an area where the established infrastructure in the natural gas sector creates favorable conditions for the gradual integration of the hydrogen value chain.

In this context of energy transformation, the Northern Rio de Janeiro region assumes a strategic role, not only due to its well-established operational system in the oil and gas industry but also because of its economic and territorial significance. The municipality of Macaé, for example, located in this region, underwent profound structural changes beginning in the 20th century (MACAÉ, 2022). The main turning point occurred in the 1970s, with the discovery and intensification of oil exploration in the Campos Basin. From that point on, the local economy, previously based on agriculture, fishing, and small-scale industrial activities, began to emerge as a national hub for the energy sector, hosting major operational, logistical, and technical support facilities (MACAÉ, 2022).

The reuse of existing infrastructure, previously used for the transport of hydrocarbons, is a strategy to make low-carbon hydrogen projects technically feasible and reduce their costs (WILCOX et al., 2024). Some global projects have already adopted the reuse of existing gas pipelines, such as the case of countries participating in the European Hydrogen Backbone project, which transport hydrogen in small fractions alongside natural gas ( ). This reuse method could be a strategic point of interest for companies like Petrobras, as it aligns the offshore decommissioning agenda of facilities with the implementation of a low-carbon hydrogen supply chain, training specialized labor to decontaminate and remediate negative impacts. Reuse would not only reduce decommissioning costs but could also contribute to the socio-environmental context (WILCOX et al., 2024). Figure 04 shows the state of Rio de Janeiro, highlighting the Northern Fluminense Mesoregion, a region of strategic interest for low-carbon projects.

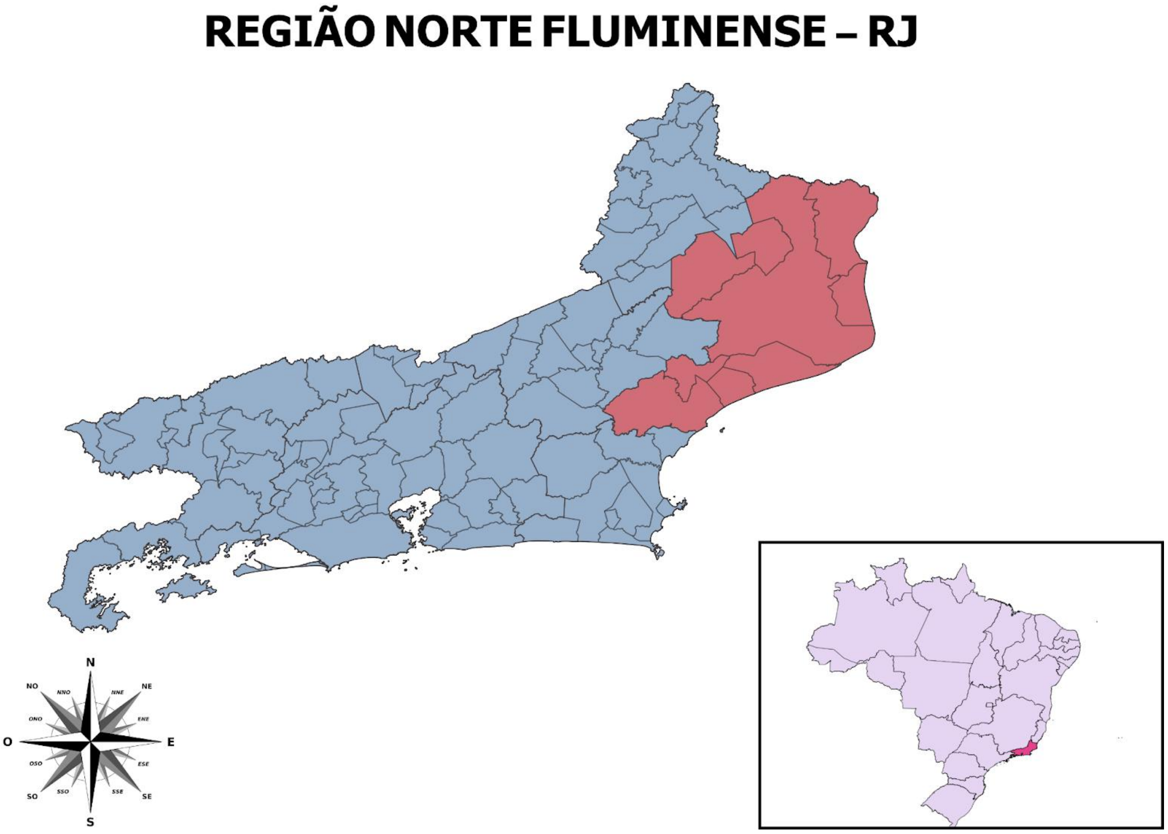
REGIÃO NORTE FLUMINENSE – RJ

Figure 04: Map of the State of Rio de Janeiro highlighting the Northern Fluminense Mesoregion. Source: Author's own work, 2026.

The Northern Fluminense region stands out as strategic for the energy transition in the state of Rio de Janeiro, especially regarding the adaptation of natural gas infrastructure for hydrogen transport and storage. The Port of Açu, located in the municipality of São João da Barra, is a private port that has invested in renewable energy generation projects, such as wind and solar power, leveraging the natural resources available in the region. Its infrastructure was designed to enable the implementation of new technologies, facilitating the integration of renewable sources into the national energy system (PORTO DO AÇU, 2025).

In addition, the Northern Rio de Janeiro region is home to an extensive network of gas pipelines, 101 km long and 20 meters wide, transporting 10 million m³/day of natural gas (EPE, 2022). This pipeline network connects key assets, such as the Cabiúnas Terminal (TECAB/TEPOR), the Duque de Caxias Refinery (REDUC), and the Gaslub Hub in Itaboraí, establishing the state as a natural gas logistics hub and a potential driver for the hydrogen value chain (FIRJAN, 2021; EPE, 2023).

Thus, the existing infrastructure not only ensures the transport of natural gas produced in the various pre-salt routes (Routes 2, 3, 4b, 5b, and 6b), Figure 5, but also serves as a support base for future adaptations focused on hydrogen, reinforcing the role of Northern Rio de Janeiro in Brazil's energy transition (EPE, 2023; FIRJAN, 2021).

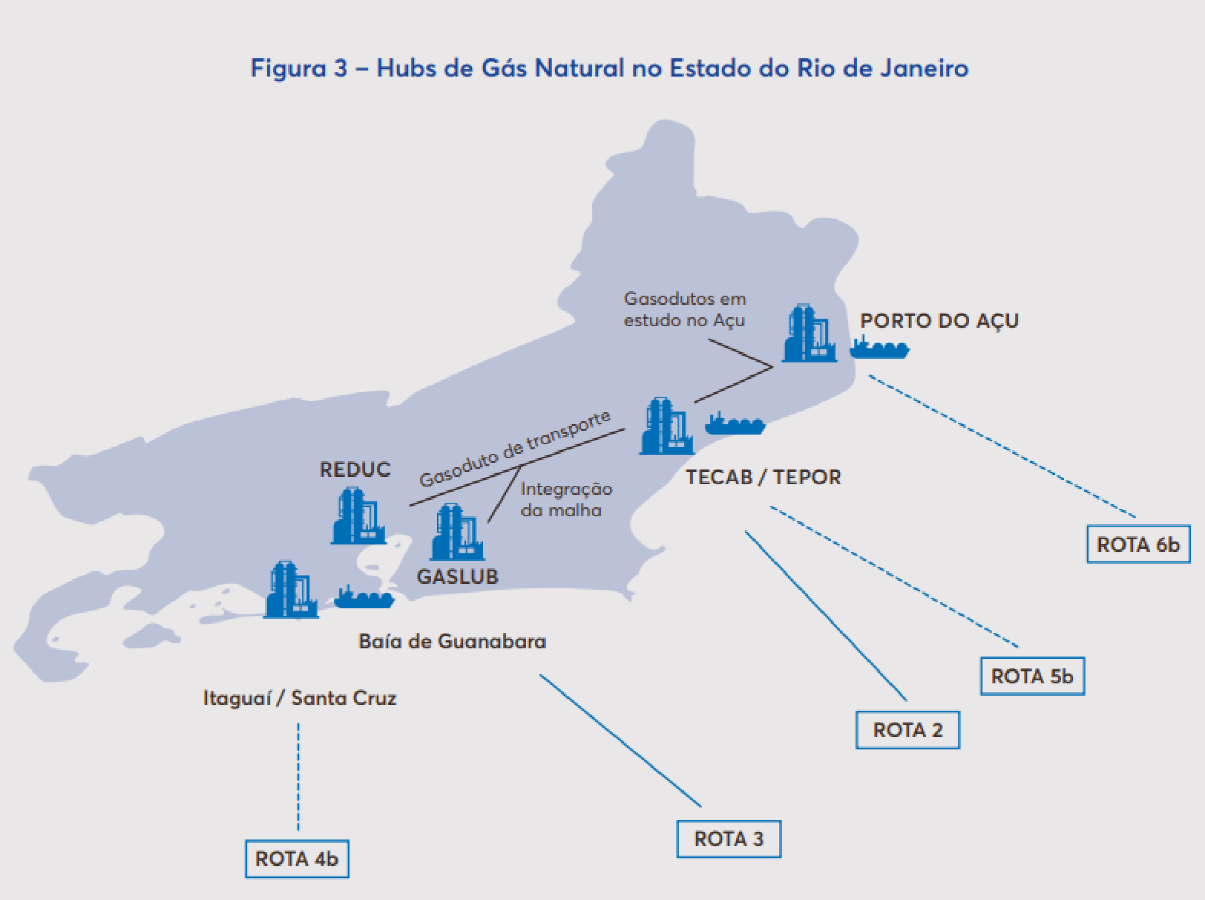

Figure 05: Natural gas pipeline infrastructure in the State of Rio de Janeiro. Source: FIRJAN, 2021.

The image above highlights the existing pipeline network and processing hubs. The concentration of pipelines in this area reinforces its strategic potential for the energy transition and the implementation of hydrogen transport and storage technologies (EPE, 2019). In this context, official data from the National Agency of Petroleum, Natural Gas, and Biofuels indicate a continuous increase in natural gas production in Brazil over the past 15 years, thus highlighting the population's dependence on fossil fuels, as shown in Table 03 (ANP, 2024).

As can be seen in Table 03, domestic natural gas production has shown steady growth over the past 15 years. This dependence underscores the importance of energy transition strategies, such as the use of low-carbon hydrogen, reducing consumption of fossil fuels, and diversifying the national energy mix.

In the case of Macaé, this intensification of production has triggered significant environmental impacts. Among the main impacts are the degradation of coastal and marine areas due to offshore activities, including accidental oil spills, effluent discharge, and increased vessel traffic, which directly affect coastal ecosystems and interfere with artisanal fishing activities (IBAMA, 2019). There is also pressure on water resources due to population growth, resulting in increased consumption of drinking water and greater transport of sediments and contaminating e s into water bodies, in addition to the discharge of domestic and industrial sewage without proper treatment, which may lead to a decline in water quality (COSTA, 2018).

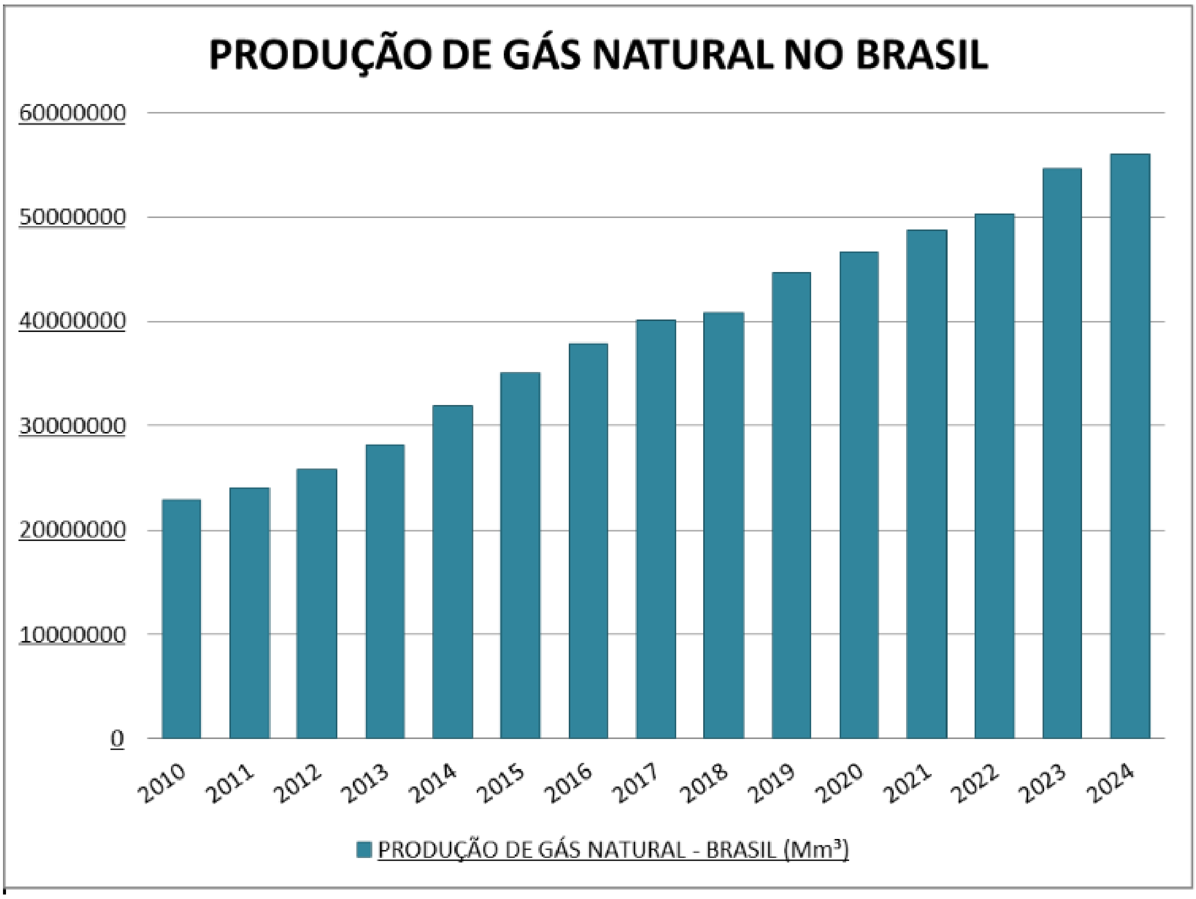

Table 03: Natural Gas Production in Brazil over the past 15 years. Data retrieved from the ANP website, 2024, own production

Another consequence of this process was the removal of native vegetation, particularly sandbank ecosystems, and habitat fragmentation, leading to biodiversity loss in previously preserved areas (MACAÉ, 2022). Finally, this entire process of transforming Macaé into an energy hub also contributed to air pollution, due to the burning of gases and the increase in heavy vehicles on the roads caused by the growing influx of service providers associated with the oil and gas sector, directly affecting the surrounding population and the ecological balance (IBAMA, 2019).

According to the 2013–2022 Ten-Year Plan for the Expansion of the Pipeline Transportation Network (PEMAT), the decisions made when mapping out new routes for pipeline construction aim to minimize the socio-environmental impacts caused by the process, giving preference to routes close to existing roads, thereby avoiding deforestation and reducing the clearing of native vegetation, in addition to being areas less prone to erosion (EPE, 2013). Similarly, the storage phase, which complements the transportation infrastructure, must be planned with equal technical and environmental rigor, given that hydrogen must be maintained under specific pressure and temperature conditions to ensure its viability and safety.

Based on the principle of sustainable planning and the utilization of existing infrastructure, the Northern Rio de Janeiro region could benefit from European experience by adopting a hybrid infrastructure model, as is the case in some European countries, using a combination of the retrofitting of existing gas pipelines with underground storage in salt domes and unused reservoirs. Given its solid foundation, this configuration would make optimal use of the existing infrastructure, reducing costs associated with the installation of new pipelines while minimizing environmental impacts. However, it is essential that such interventions be accompanied by risk analyses, contingency plans, and environmental permitting procedures tailored to the regional context.

The hydrogen economy in Northern Rio de Janeiro depends on the ability to integrate the region's existing infrastructure with the new demands of the energy transition. Because it has a well-established infrastructure, characterized by the presence of major energy, port, and industrial projects, such as the Cabiúnas Terminal (TECAB), the Port of Açu with its extensive pipeline network, along with the Gas Production Anticipation Program (PLANGAS), enables logistics that can be leveraged for the transport and storage of hydrogen, reducing implementation costs and minimizing the environmental impacts resulting from the construction of new pipelines (EPE, 2022; BRAZIL, 2011).

In the regional context, the adaptation of existing gas pipelines emerges as a more viable alternative in the short and medium term, following trends in European countries according to data presented by *the European Hydrogen Backbone* (2024). According to Witkowski et al. (2018), the controlled blending of hydrogen with natural gas, at concentrations of up to 15%, can be done without major changes to the structural integrity of the pipelines; however, appropriate materials and continuous monitoring are necessary.

Regarding storage in the medium and long term, one option emerging as a strategic solution is underground hydrogen storage (UHS). Due to the regional geology, saline formations, and depleted natural gas fields in the Campos Basin, the region offers favorable conditions for safe, large-scale storage (CIOTTA et al., 2023). This approach would reduce the impacts and risks associated with surface storage and long-distance transportation, and would also provide greater supply stability.

However, its implementation requires careful environmental and territorial assessments, particularly in areas of high ecological sensitivity, as the risk of habitat fragmentation, soil contamination, leaks, and urban pressure on protected areas can pose challenges that must be mitigated through strategic planning, preventive environmental licensing, and ecological compensation measures (IBAMA, 2021; BRAZIL, 1986).

Forms of hydrogen storage

Establishing a hydrogen economy in Brazil requires a robust and well-structured infrastructure capable of meeting the demands of large-scale production, storage, and distribution. For this technology to be developed sustainably in the Northern Rio de Janeiro region, minimizing the resulting impacts, thorough studies must be conducted that address technical, socioeconomic, and environmental perspectives (GONÇALVES et al., 2025). Table 04 presents a comparison of the main advantages and disadvantages of hydrogen transport and storage technologies, highlighting the critical points to be considered for the implementation of this infrastructure.

Table 04: Comparative table of the advantages and disadvantages of transportation and storage technologies.

COMPARATIVE TABLE OF STORAGE TECHNOLOGIES: ADVANTAGES VS. DISADVANTAGES				
TECHNOLOGIES	**DESCRIPTION**	**ADVANTAGES**	**DISADVANTAGES**	**RECOMMENDED SCALE**
Compressed gas	Storage at 350–700 bar in cylinders or pressurized tanks	Logistical flexibility: road transport	Volume limit, high cost per kilogram	Small and medium scale
Gaseous hydrogen in salt caverns	Injection into deep geological formations	Large storage capacity, geological safety	Requires suitable formations, high initial investment	Large scale, seasonal storage
Depleted reservoirs	Reuse of depleted oil and gas fields	Reuse of depleted fields	Geological integrity risk, need for seismic evaluation	Large scale
Glass microspheres	Storage in porous glass microspheres containing H_2	High safety, can operate at high temperatures, high storage density	Technology still experimental, low adsorption, requires heating to discharge	Research and experimental applications
MOF (*Metal-Organic Framework*)	Porous structures that adsorb H_2	Large surface area, high porosity, potential for high density	Technology still under development, high cost, low adsorption	Advanced research, medium-scale future outlook
Metal hydrides	Chemical absorption storage in metals	High volumetric density, low-pressure operation	High mass, slow kinetics, high cost	Stationary applications and specific niches
Liquid hydrogen in cryogenic tanks	Cooled to -253°C, stored in insulated tanks	Storage at fixed locations, higher energy density	High cost, strict thermal insulation, boil-off losses	Medium and large scale (Port terminals, export)

Source: Author's own work, data taken from IEA (2019); IBAMA (2021); SHARMA et al. (2023); YANG et al. (2023); CHEN (2025).

Hydrogen embrittlement

With the growing global interest in hydrogen as an energy carrier, significant challenges related to its logistics chain have also emerged, particularly in transportation and storage processes. Hydrogen requires specific equipment and procedures for its handling. Because it is a very light gas, it can permeate certain materials, making the selection of pipeline materials critical to prevent failure (IEA, 2019).

One of the main technical risks associated with these stages concerns the prolonged exposure of metallic materials to high-pressure environments containing hydrogen, a condition that can compromise the structural integrity of the pipelines. This phenomenon, known as hydrogen *embrittlement* (HE), results in a loss of ductility, promotes the nucleation and propagation of cracks, and consequently reduces the service life of gas pipelines, increasing the probability of fatigue failures (LIU et al., 2023).

According to Liu et al. (2023), hydrogen embrittlement can occur through three distinct mechanisms: (i) internal hydrogen embrittlement (IHE), (ii) *hydrogen environment embrittlement* (HEE), and (iii) *hydrogen reaction embrittlement* (HRE). The impacts of embrittlement can cause serious damage to the environment. The loss of toughness and fracture resistance can lead to cracks and fissures, culminating in failures, leaks, and even explosions, a risk that is particularly heightened in gas pipelines due to their greater length, which makes constant monitoring difficult (NAQUASH et al., 2022).

In addition, the study by Liu et al. (2023) highlights that, although high-strength steels such as API grades X70 and X80 are widely regarded as promising for long-distance hydrogen transport, these materials exhibit greater susceptibility to hydrogen embrittlement when compared to lower-strength metal alloys. This characteristic requires attention during the material selection process, as well as in the development of mitigation strategies aimed at ensuring the safety and durability of the associated infrastructure.

The susceptibility of metallic materials used in pipelines, such as API 5L X80, highlights the need for stricter control of operating conditions (BALLESTEROS et al., 2012). In addition to embrittlement, corrosion occurs mainly in soil environments, which may contain microorganisms that influence steel degradation (QUEIROZ et al., 2016). Clay soils tend to be more aggressive to pipelines than sandy soils, which ultimately affects the integrity of the materials (GONÇALVES et al., 2025).

With the growing interest in hydrogen in the energy transition, there has been an increase in research aimed at improving the materials used in piping. Currently, alloys more resistant to hydrogen and metallic compounds for pressurized tanks are being studied, with a focus on mechanical strength and hydrogen diffusion (NAQUASH et al., 2022).

Health and Safety Risks

With the Industrial Revolution and advances in technology, an increase in occupational accidents and illnesses became evident, necessitating the implementation of preventive measures. Risk management is of fundamental importance to ensure the physical safety of workers and the preservation of environmental sustainability (RUPPENTHAL, 2023).

The need to expand the transmission pipeline network has become increasingly evident, necessitating its implementation in populated areas as well. Regulations regarding transmission pipelines were primarily focused on technical issues such as construction, operation, and maintenance , while other sectors were neglected, such as the impact generated by decisions regarding land use and public safety, in addition to posing risks to the population and potentially increasing the vulnerability of pipelines to external damage due to accidental excavations (TRANSPORTATION RESEARCH BOARD, 2004).

However, H_2 gas as a substance is neither toxic nor poses a risk to human health under normal conditions. Nevertheless, it presents a high risk of flammability and explosion, which are critical factors for operational safety. H_2 is highly flammable when in contact with air. On the other hand, cryogenically cooled liquid hydrogen (in a cryogenic state) can cause severe frostbite (PUBCHEM, 2025).

Consequently, risk analysis can be conducted through safety inspections, accident investigations, and the creation of flowcharts, aiming to detect irregularities, identify the causes of accidents, propose corrective measures, and prevent recurrence of the accident; flowcharts help map processes and identify critical points (RUPPENTHAL, 2023).

Business risks can be classified into speculative risks, involving the risk of losses or gains, and pure risks, where there are only losses, which may affect property, people, and the environment (RUPPENTHAL, 2023).

According to data analyzed in the report *Transmission pipelines and use: A risk-informed approach - Special Report 28* (TRANSPORTATION RESEARCH BOARD, 2004), between 1999 and 2001 the main causes of accidents were construction defects, corrosion, operational failures, and third-party damage due to excavation, with the latter accounting for approximately 24% of incidents in natural gas pipelines.

Results and Discussion

Based on the analyses conducted, it is observed that the hydrogen economy in Brazil is still in its early stages, although it shows strategic potential in regions historically shaped by the energy sector, such as the Northern Rio de Janeiro region. The literature and documentary review on hydrogen transport and storage identified key factors influencing technical feasibility, technological challenges, and the socio-environmental impacts involved in the transition to a low-carbon economy.

Since the 1970s, the city of Macaé and adjacent municipalities have established themselves as a major national energy hub due to the expansion of the oil and gas industry, with direct effects on urban infrastructure, economic dynamics, and territorial configuration (MACAÉ, 2022; FONTOURA et al., 2023). The pipeline network, approximately 101 km long and transporting about 10 million cubic meters of natural gas daily, is an essential component of this system. Although this network has the potential to be adapted for hydrogen transport, such a conversion requires careful consideration of technical risks, such as material degradation and the need for rigorous operational safety standards (EPE, 2022).

International projections indicate that clean hydrogen production could reach between 18 and 48 million tons annually by 2030, depending on technological advancements and the level of commitment from public policies (MCKINSEY & COMPANY, 2024).

Regarding storage, systems based on pressurized or cryogenic tanks offer high efficiency, with discharge rates that can reach up to 99% (IEA, 2019). However, the inherent limitations of hydrogen, whose energy density is about 15% that of gasoline, require volumes up to seven times larger to store the same amount of energy, which imposes significant logistical constraints. For this reason, large-scale underground solutions, such as salt caverns and depleted oil and gas reservoirs, have gained prominence. This is because they combine operational safety, technical robustness, and economic vi . The use of salt caverns has a well-established history dating back to the 1970s and 1980s in countries such as the United Kingdom and the United States, particularly in the chemical sector (IEA, 2019).

With regard to pipeline transportation, hydrogen embrittlement (HE) represents one of the main technical challenges. High-strength metal alloys—such as API X70 and X80 steels—can experience a loss of ductility and a greater propensity for internal cracking when exposed to hydrogen, compromising their structural integrity (LIU et al., 2023; NAQUASH et al., 2022). Furthermore, accidents in natural gas pipelines are frequently associated with corrosion, construction defects, unauthorized excavations, and a lack of preventive maintenance, reinforcing the need for continuous inspection and advanced monitoring technologies (TRANSPORTATION RESEARCH BOARD, 2004; RUPPENTHAL, 2023).

The assessment of socio-environmental impacts related to the energy infrastructure in the Northern Rio de Janeiro region highlights the need for an integrated approach to territorial planning. The expansion of industrial activities and the pipeline network in Macaé has resulted in the degradation of coastal areas, fragmentation of ecosystems, contamination of water bodies, and increased air pollution, according to various studies and institutional reports (COSTA, 2015; 2018; 2019). Thus, any expansion of hydrogen-related infrastructure must align with the guidelines of the Transportation Network Expansion Plan (PEMAT), incorporating measures for erosion control, selective vegetation removal, and protection of environmentally sensitive areas (EPE, 2013).

In summary, the results indicate that the feasibility of implementing a hydrogen supply chain in the region depends both on the maturation of production, storage, and transportation technologies and on integrated territorial management, guided by the mitigation of socio-environmental impacts and the safety of existing infrastructure.

Conclusion

The purpose of this article was to identify and assess the environmental, social, and socioeconomic impacts resulting from the implementation of hydrogen transportation and storage infrastructure in the Northern Rio de Janeiro region. Based on the international and national overview presented, it is possible to establish a comparative framework for the technical analyses conducted in different countries. A review of scientific articles focused on the hydrogen sector reveals exponential growth over the years, particularly after 2020; however, there remains a lack of articles in specific areas such as hydrogen embrittlement and studies addressing the impacts of infrastructure construction in the Northern Rio de Janeiro region.

This research has identified and articulated the main technical, environmental, and socioeconomic factors that determine the feasibility of implementing infrastructure for hydrogen transport and storage in the Northern Fluminense region. The integrated analysis of the data shows that, although the region offers logistical and structural advantages, the transition to a hydrogen-based economy requires a multisectoral approach grounded in scientific, technological, and regulatory criteria.

Notably, the region's logistical potential is bolstered by an already established energy infrastructure, proximity to strategic consumer centers, and a history of technical and industrial development linked to the oil and gas sector. However, making this new energy matrix viable requires significant investments in upgrading pipelines and reconfiguring operational systems. The replacement or adaptation of materials and equipment, in addition to the technical training of the professionals involved, is an indispensable condition for ensuring asset integrity and operational efficiency.

Among the risks analyzed, *hydrogen embrittlement* (HE) stands out as one of the critical aspects, mainly due to hydrogen's ease of penetrating the interior of metallic structures. The phenomenon known as atomic permeation occurs when hydrogen molecules dissociate on the metal surface, penetrating the microstructure and accumulating in high-stress regions, which contributes to the formation of microcracks, thereby contributing to hydrogen embrittlement (LIU et al., 2023).

This condition necessitates the use of high-strength materials, as well as the implementation of robust inspection, predictive maintenance, and risk management plans, in accordance with international safety standards and the technical recommendations of the specialized literature (LIU et al., 2023; NAQUASH et al., 2022).

With regard to storage, geological solutions are emerging as strategic alternatives on an industrial scale. The use of salt caverns and depleted reservoirs, already tested in countries such as the United States and the United Kingdom since the mid-20th century (IEA, 2019), offers significant advantages in terms of thermal stability, cost-effectiveness, and reduced surface footprint, in addition to ensuring greater operational safety in the face of the volumetric limitations of conventional high-pressure and cryogenic methods.

However, the expansion of this infrastructure requires heightened attention to the resulting socio-environmental impacts. The Northern Rio de Janeiro region, particularly the city of Macaé, already has a history of environmental degradation linked to oil and gas exploration, including contamination of water bodies, fragmentation of natural habitats, and overburdening of urban and coastal areas (COSTA, 2015; 2018; 2019). The introduction of new pipeline routes and storage facilities must, therefore, respect the principles of sustainable development, ensuring compliance with established legal guidelines, such as CONAMA Resolution No. 001/1986, and the parameters defined by regulatory agencies such as ANP, IBAMA, and EPE (EPE, 2013).

Given this situation, the following is recommended:

- The conduct of laboratory and field technical tests aimed at evaluating hydrogen embrittlement in existing pipelines in the region;
- Encouraging the development and application of metallic or composite materials with high resistance to hydrogen permeation and degradation;
- The planning of transportation routes that prioritize already developed areas and avoid permanent preservation zones, respecting local environmental and social characteristics;
- Requiring consistent and participatory environmental impact studies in licensing processes, comprehensively addressing the social, ecological, and occupational aspects of projects;
- The implementation of continuous monitoring routines, technical training, the development of operational protocols, and emergency response strategies, with a focus on accident prevention and the protection of human and environmental health.

According to the analyzed literature, institutions responsible for pipeline infrastructure—such as regulatory agencies, operating companies, and research centers—should promote technical, laboratory, and field tests aimed at assessing hydrogen embrittlement. Such recommendations are not part of the methodological scope of this study, which is exclusively exploratory and descriptive in nature, but they reflect technical gaps identified throughout the research.

Furthermore, the existence of natural hydrogen reservoirs in the Northern Rio de Janeiro region is currently being assessed, offering potential for local exploitation at reduced costs and contributing to the acceleration of the energy transition (ARROUVEL, 2025).

In this context, the integration of technological innovation, territorial planning, and environmental justice is essential for hydrogen to fulfill its role as a driver of sustainable development, especially in regions historically marked by the intensive exploitation of natural resources.

It is concluded that the Northern Rio de Janeiro region possesses the technical, logistical, and strategic conditions necessary to establish itself as one of the country's main hubs for the hydrogen economy, enabling the gradual introduction of the hydrogen value chain. The integration of existing pipeline adaptation, the construction of dedicated pipelines, underground storage, and port infrastructure represents a significant opportunity for sustainable regional development. However, the adoption of these technologies requires integrated planning, taking into account the environmental and social characteristics of the territory, especially the presence of sensitive ecosystems and communities in areas of direct influence. The transition to the hydrogen economy will depend on coordination among the public, productive, and academic sectors and civil society, ensuring that progress occurs in a safe, participatory, and environmentally responsible manner.

Additionally, the consolidation of this infrastructure will require strengthening governance and the regulatory framework for hydrogen, necessitating the development of specific guidelines for large-scale transportation and storage. Such guidelines must address aspects such as operational and environmental safety, environmental licensing processes, and the integrated monitoring of activities.

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