International Journal of Engineering Research and Development
e- ISSN: 2278-067X, p-ISSN: 2278-800X, www.ijerd.com
Volume 21, Issue 6 (June 2025), PP 163-170

Technological Pathways for Hydrogen Production in Brazil (Gaseous, Liquid, Solid, and Hybrid): Economic Feasibility, Regulatory Challenges, and Certification in Dialogue with International Experiences

Spec. André Luiz Barros de Oliveira[1] https://orcid.org/0000-0002-2838-4208; Prof. M. Sc. Alcides Feitosa Neto[2] https://orcid.org/0009-0006-3749-3509; B. Sc. (Cand.) Ana Katherine Silveira Pereira Caracas[3] https://orcid.org/0009-0003-9374-9175; M. Sc. (Stud.) Antonio Werbiton Marinho Almeida[4] https://orcid.org/0009-0002-1904-7522; PhD. Francisco José Lopes Cajado[5] https://orcid.org/0000-0002-8824-9251; Dr. Givanildo Ximenes Santana[6] https://orcid.org/0000-0001-8337-1082; Spec. Irene Mendes Fontes[7] https://orcid.org/0009-0002-3152-6649; Profa. Spec. Isabela Maciel Taveira[8] https://orcid.org/0009-0004-0666-3662; Profa. Dra. Luisa Janaina Lopes Barroso Pinto[9] https://orcid.org/0000-0003-1505-5461; M. Sc. Márcio Carneiro Barbosa[10] https://orcid.org/0009-0003-8290-1127; Ph.D. Paulo Henrique Barbosa Sousa[11] https://orcid.org/0009-0007-1269-7860; Rickardo Léo Ramos Gomes[12] https://orcid.org/0000-0001-6101-9571; Ph. D. Student Roberto Augusto Caracas Neto[13] https://orcid.org/0000-0001-8484-411X; M. Sc. Sana Eteki Mboumena Mane[14] https://orcid.org/0009-0009-2491-1849; Prof. Dr. Tadeu Dote Sá[15] https://orcid.org/0009-0005-5575-6328, Wangler Luiz Silva Chaves[16] https://orcid.org/0009-0000-6781-8753, Willy de Souza Felix[17] https://orcid.org/0009-0005-3119-9539

[1] Postgraduate in MBA in Renewable Energy Management (IEL/FBUNI); [2] Master's degree in Economics from the Federal University of Ceará; [3] Undergraduate Student in Chemical Engineering; [4] Master's student in Administration and Controllership at UFC; [5] Ph.D. in Agricultural Biotechnology (RENORBIO – UFC; [6] Ph.D. in Genetics, Conservation, and Evolutionary Biology National Institute of Amazonian Research, Manaus-AM, Brazil; [7] Postgraduate Degree in Criminal Law from UniAteneu University Center; [8] Specialist in Wind Energy – CTGás; [9] Ph.D. in Development and Environment – Federal University of Ceará (UFC); [10] M. Sc. in Military Sciences – Army Command and General Staff School; [11] Ph.D. in Educational Sciences, FCSA (DINTER Program); [12]Doctorate in Biological Sciences - FICL; Master's in Phytotechnics - Federal University of Ceará; [13] Doctoral Student at the Academy of the National Institute of Industrial Property; [14] Master of Monetary and Financial Economics; [15] Prof. Dr. in Regional Development from the University of Barcelona; [16] Postgraduate in MBA in Renewable Energy Management (IEL/FBUNI); [17] (Master of Business Administration (MBA) in Project Management (FGV)
Corresponding Author: Rickardo Léo Ramos Gomes

ABSTRACT
The growing demand for sustainable energy sources has sparked global interest in hydrogen as a strategic vector for decarbonization, particularly in countries with high renewable potential, such as Brazil. In this context, the present study adopted a qualitative and applied research approach, employing bibliographic and documentary procedures, with an emphasis on official sources, up-to-date information, reports from international organizations, and the analysis of 47 peer-reviewed scientific articles specializing in the topic. The primary objective was to investigate the main challenges and opportunities for the consolidation of the hydrogen economy in Brazil, with a focus on technological pathways, economic feasibility, and certification mechanisms. The findings indicate that the adoption of a hydrogen-based economy in Brazil requires collaborative actions between the public and private sectors, as well as the establishment of regulatory frameworks that ensure predictability

and legal certainty. The achievement of a more sustainable and resilient energy matrix depends, above all, on the integration of technological innovations, financial incentives, and engagement strategies within the international context—factors that were thoroughly examined in this research.

Keywords: *hydrogen, energy matrix, collaborative actions, certification mechanisms.*

Date of Submission: 15-06-2025 Date of acceptance: 30-06-2025

I. INTRODUCTION

In recent decades, the search for clean and sustainable energy sources has become a global priority due to the climate emergency and the urgent need for a transition to a low-carbon economy. In this context, hydrogen has emerged as a strategically important energy vector, with the potential to enable decarbonization across various industrial sectors and transportation systems. Given its abundant natural resources and the predominance of a largely renewable energy matrix, Brazil is in a privileged position to advance several technological pathways for hydrogen production. These pathways—encompassing gaseous, liquid, solid, and hybrid processes—offer multiple opportunities for energy exploration, while also posing significant challenges related to economic feasibility, regulation, and certification.

This study is based on a qualitative approach, adopting bibliographic and documentary research methods. These procedures enabled the collection, analysis, and systematization of relevant technical-scientific, regulatory, and institutional information regarding hydrogen production, both nationally and internationally.

The general objective of this study is to analyze the main technological routes for hydrogen production in Brazil, assessing their economic feasibility and the regulatory challenges associated with national certification, in comparison with international experiences. To achieve this goal, the following specific objectives were established:

- To map and characterize the main technological routes for hydrogen production in Brazil—gaseous, liquid, solid, and hybrid—considering technical, environmental, and applicability aspects within the national context;
- To investigate the economic feasibility of the different hydrogen production routes in Brazil, considering infrastructure, production, storage, and distribution costs;
- To assess regulatory challenges related to hydrogen certification in Brazil, comparing them to current international standards adopted by leading countries in the energy transition, such as Germany, Australia, Benelux, Japan, and the European Union.

The article is structured into four main sections. The first introduces the topic and outlines the study's objectives. The second section presents the methods and materials employed in the research. The third section comprises the theoretical framework, organized into three subsections: (1) technological pathways for hydrogen production in Brazil; (2) economic feasibility of the technological routes; and (3) regulatory challenges and certification, with a focus on international experiences. Lastly, the fourth section presents the final considerations, summarizing the study's main conclusions and recommendations.

II. MATERIAL AND METHODS

The methodology adopted for this research was of a qualitative nature, as this approach provides meaningful foundations for the in-depth analysis of social and environmental phenomena related to renewable energy sources. Qualitative research enables the understanding of meanings, interpretations, and contexts—elements that are fundamental to the analysis of documents and technical publications related to energy policies, sustainability, and technological innovation. According to Valles (2007), qualitative approaches foster methodological reflection that goes beyond the mere collection of data, promoting an investigative practice grounded in the understanding of the multiple dimensions of social reality.

Two investigative methods were employed: bibliographic research and documentary research. The literature review is essential for outlining the current state of knowledge on the topic, allowing the researcher to engage in dialogue with various authors and to identify gaps that still require further investigation. Pizzani et al. (2012) emphasize that bibliographic research is a practice that demands rigor in the selection and analysis of sources, thus promoting the development of critical knowledge. Documentary research, according to Cellard (2019), is a relevant technique for analyzing official, institutional, or technical documents, as it enables the investigation of records that reveal political actions, regulatory frameworks, and strategic decisions within specific contexts. Both strategies proved to be complementary in the execution of this study, providing a robust foundation for the analyses conducted.

In total, 47 sources published between 2019 and 2025 were consulted, including 12 official documents, four of which originated in Brazil. The diversity of sources reflects the research's commitment to compiling current and significant information within both national and global contexts. The selection of recent documents and the combination of various types of materials aim to ensure the accuracy and reliability of the study, establishing a relevant theoretical and practical foundation for the improvement of future public policies aimed at expanding renewable energy in Brazil. The overarching goal is to offer solid foundations to guide strategic decision-making in favor of a more sustainable and equitable energy model.

III. THEORETICAL FRAMEWORK

3.1 Technological Pathways for Hydrogen Production: Characteristics, Efficiency, and Applications in the Brazilian Context

Hydrogen has emerged as a strategic vector in the global energy transition, produced through various technological routes that differ in terms of raw materials, energy efficiency, technological maturity, environmental impacts, and integration potential with renewable sources. In Brazil, the National Council for Energy Policy (Conselho Nacional de Política Energética – CNPE) has identified hydrogen as one of the country's priority areas for research and development (R&D), with the objective of guiding resource allocation (Brasil, 2021a, 2021b). Given Brazil's energy diversity and recent advances in climate-related policies, it is essential to map and understand gaseous, liquid, solid, and hybrid production routes, considering not only technical and economic feasibility but also the nation's unique environmental and territorial characteristics.

Recent studies have shown that the efficiency of different hydrogen production routes is highly influenced by regional contexts and public policies aimed at decarbonization (Ji & Wang, 2021; Yu, Wang, & Vredenburg, 2021). Currently, gaseous hydrogen production, particularly via natural gas reforming combined with carbon capture and storage (CCS), is a consolidated and widely adopted method in countries such as Japan, the United States, and Germany. Although its application remains limited in Brazil, there is potential for gradual adoption, especially in regions with existing gas infrastructure and aligned with carbon capture policies (Aramco, 2020; Siffert & Rocha, 2025).

Water electrolysis, considered the primary liquid route, has gained prominence as a sustainable alternative when combined with abundant renewable energy sources such as solar and wind power, which are expanding rapidly in Brazil (International Renewable Energy Agency [IRENA], 2020). In terms of solid-state routes, cryogenic storage stands out for its promising applications in transportation and hydrogen export, although it still entails high operational costs. Hybrid pathways, including hydrogen production through biomass gasification combined with electrolysis, have been investigated as integrated solutions aligned with circular biorefinery approaches (Chatterjee & Mohan, 2021; Kant et al., 2021).

Table 1 – Below summarizes these pathways, their main characteristics, maturity levels, and applicability within the Brazilian context.

Technological Route	Example	Energy Efficiency (approx.)	Technological Maturity	Potential in Brazil
Gaseous	Natural gas reforming with CCS	60–70%	High	High in regions with gas infrastructure; strong demand for carbon regulation
Liquid	Water electrolysis (solar/wind energy)	45–70%	Medium-High	Very high; compatible with renewable energy expansion
Solid	Cryogenic storage	Depends on the source	Low-Medium	Potential in transport/export, but requires infrastructure investment
Hybrid	Biomass + electrolysis (biorefineries)	50–65%	Medium	Promising in areas with biomass surplus and bioeconomy policies

Source: Adapted from IRENA (2020); Chatterjee and Mohan (2021); Siffert and Rocha (2025); Ji and Wang (2021).

The joint evaluation of these pathways leads to the conclusion that, although the gaseous route exhibits high maturity and well-established short-term applications, the liquid and hybrid routes demonstrate greater alignment with Brazil's renewable energy matrix and its climate neutrality commitments. Furthermore, the development of hybrid pathways and advancements in solid-state storage technologies may enhance the integration of Brazilian hydrogen into international markets, particularly as certification and labeling guidelines related to low carbon become increasingly stringent (Espitalier-Noël et al., 2023; Bonnet-Cantalloube et al., 2023). Therefore, the formulation of a cohesive public policy and the promotion of investments in Research, Development, and Innovation (R&D&I) are essential for establishing a competitive and sustainable national model.

3.2 Economic Analysis of the Hydrogen Value Chain: Costs, Risks, and Market Opportunities

The economic viability of the various technological pathways for hydrogen production in Brazil is influenced by multiple factors, including the cost of raw materials, the availability of infrastructure, the investments required for storage and distribution, as well as the current incentive policies in place. Water electrolysis, powered by renewable sources such as solar and wind, has emerged as one of the most promising options in the Brazilian context, particularly in the Northeast region, where the energy potential is significant and the costs associated with renewable electricity are below the global average (Fussuma et al., 2024; Ministry of Mines and Energy [MME], 2021). However, the high initial investments in electrolyzers, combined with logistical constraints, continue to pose challenges to its competitiveness compared to other methods, such as natural gas reforming with carbon capture (Dawood et al., 2020).

Recent studies indicate that the levelized cost of green hydrogen in Brazil could reach competitive values by 2030, provided there is coordination among public policies, fiscal incentives, and private investments in infrastructure (Confederação Nacional da Indústria [CNI], 2022; Hinicio et al., 2023). Gilles and Brzezicka (2022) state that investment incentives are intrinsically linked to the predictability of regulations and mechanisms aimed at risk mitigation, including long-term contracts and minimum price guarantees. The absence of a structured network for hydrogen transport and storage also increases the total operational cost, impacting the return on investment. The table below (Table 2) summarizes a comparative analysis of the projected costs of the main hydrogen production pathways in Brazil, considering economic and technological factors.

Table 2 – Economic Comparison of the Main Hydrogen Production Pathways in Brazil

Technological Pathway	Estimated Production Cost (USD/kg H_2)	Infrastructure Cost (USD/kg H_2)	Economic Risks	Expected Return (Horizon 2030)
Electrolysis with solar/wind energy	2.2 – 3.6	1.0 – 1.5	High exchange rate volatility	High (with exportation and fiscal incentives)
Natural gas reforming + CCS	1.5 – 2.2	0.8 – 1.2	Regulatory and environmental uncertainty	Medium (dependent on carbon pricing)
Biomass integrated with electrolysis	2.8 – 4.0	1.3 – 1.8	Current low industrial scale	Low to medium (depending on technological advances)
Offshore wind + Battolyser	3.0 – 4.5	1.5 – 2.2	High initial cost	High (for exportation via integrated ports)

Source: Data adapted from Fussuma et al. (2024), Bristowe and Smallbone (2021), Jenkins et al. (2022), Hinicio et al. (2023), and the International Energy Agency (IEA, 2024).

The economic attractiveness of hydrogen produced in Brazil is equally related to its participation in global value chains, which entails challenges such as international certification, port logistics, and compliance with environmental regulations. According to Quitzow et al. (2023), the implementation of hydrogen hubs in Brazilian ports, particularly in the Northeast region, has the potential to reduce logistical costs and increase competitiveness relative to markets such as Europe and Asia. Similarly, as highlighted by the 2023–2025 Triennial Work Plan (Ministry of Mines and Energy [MME], 2023), the competitive advantage arising from the installation of hydrogen production plants within port complexes (hubs) that also include industrial plants was emphasized. In Brazil, current port complexes with this profile are located in Pecém-CE, Suape-PE, Açu-RJ, and Rio Grande-RS (Oliveira, 2022). Concurrently, integrated public policies, such as the guidelines of the National Hydrogen Program (PNH2), are essential to mitigate the economic and regulatory constraints that currently hinder the expansion of low-carbon technologies. In this context, development opportunities depend on the interaction between the state, industry, and research centers, as also stressed by Ribeiro Filho, Tahim, and Veras (2023) in light of the triple helix model. As an advantage, hydrogen production and export could position Brazil as a provider of decarbonization solutions for other nations (Brazil, 2023).

It should be emphasized that the environmental impacts associated with green hydrogen (H2V) production cannot be overlooked. Therefore, Table 3 is presented below, summarizing the main environmental impacts related to green hydrogen production via electrolysis processes, highlighting liquid, solid, and gaseous waste, as well as general aspects that affect the sustainability of this production chain.

Table 3 – Environmental Impacts of Green Hydrogen Production by Electrolysis: Waste, Critical Aspects, and Key References

Category	**Environmental Impacts and Negative Aspects**	**Contributing Authors**
Liquid Waste	- High consumption of purified water (9 to 15 L/kg of H_2), putting pressure on water resources. - Generation of chemical effluents (alkalis, catalysts). - Waste from purification processes.	Li et al. (2021); Mehmeti et al. (2024); Bareiß et al. (2022)

Category	Environmental Impacts and Negative Aspects	Contributing Authors
Solid Waste	- Disposal of electrolyzers and components (membranes, electrodes, rare metals). - Waste generation from mining of raw materials (iridium, platinum, lithium). - Waste from renewable infrastructure.	Sherif et al. (2023); Lee et al. (2021); Al-Qahtani et al. (2021)
Gaseous Waste	- Indirect GHG emissions during manufacturing and transportation of equipment. - Emissions from auxiliary processes (compression, storage). - Risk of H_2 leakage.	Derwent et al. (2006); Palmer et al. (2022); Al-Qahtani et al. (2021)
Other General Aspects	- High initial carbon footprint from infrastructure construction. - Land use for solar/wind farms, impacting ecosystems. - Low energy efficiency (60–80%). - Environmental costs of component recycling.	Mehmeti et al. (2024); Palmer et al. (2022); Sherif et al. (2023)

Sources: Mehmeti et al. (2024); Bareiß et al. (2022); Li et al. (2021); Palmer et al. (2022); Sherif et al. (2023); Lee et al. (2021); Al-Qahtani et al. (2021); Derwent et al. (2006).

3.3 Regulation and Certification of Hydrogen: Challenges for Brazil Regarding International Standards

The regulation and certification of green and low-carbon hydrogen represent strategic aspects to ensure the international credibility of hydrogen produced in Brazil. The lack of standardized criteria for hydrogen characterization and traceability directly impacts its acceptance in international markets, especially in the most advanced energy transition blocs. According to Abad and Dodds (2020), the precise definition of "green hydrogen" and guarantees of origin systems are fundamental to ensure transparency and traceability—qualities valued in markets such as Europe and Japan. In this regard, initiatives like CertifHy in the European Union have served as a model for the development of robust certification systems based on carbon intensity criteria, energy sources, and verification methodologies (Veum et al., 2019).

In the Brazilian context, despite the presence of early-stage regulatory initiatives, such as investigations conducted by the National Electric Energy Agency (ANEEL, 2024) and the National Hydrogen Program, significant challenges remain concerning alignment with international standards and the development of a legal framework consistent with the country's realities. Evangelista, Magalhães, and Mariani (2023) highlight that standardization in Brazil must address the difficulty of reconciling technical, environmental, and commercial frameworks, which requires interinstitutional coordination and the mobilization of key stakeholders in the energy sector. In their studies, Gabrielli and Tokarski (2024) assert that Brazil has natural comparative advantages for green hydrogen production; however, its global competitiveness will depend on the implementation of certification mechanisms accepted by purchasing countries such as Germany, Japan, and the Benelux members. This coordination should also consider advances by agencies such as the Australian Renewable Energy Agency (ARENA), which has implemented financing mechanisms tied to sustainability criteria (ARENA, 2021).

The table below summarizes the main regulatory requirements and establishes comparisons between strategies implemented by various countries and economic blocs. Table 4 – Hydrogen Certification Standards: International Comparison and Implications for Brazil succinctly presents the technical, legal, and environmental certification demands currently implemented in Germany, Japan, Benelux, the European Union, and Australia, highlighting crucial aspects that Brazil must consider to ensure competitive access to the most rigorous markets.

Table 4 – Hydrogen Certification Standards: International Comparison and Implications for Brazil

Region/Country	Certification Standard	Main Regulatory Focus	Implications for Brazil
European Union	CertifHy (Guarantee of Origin)	Traceability, carbon footprint, independent verification	Requires methodological alignment and interoperability
Germany	HoS Roadmap	Integration with decarbonization goals and energy security	Demands adjustment of national technical and regulatory standards
Japan	Green Ammonia & Hydrogen	Low CO_2 emissions, logistics chain, and final use	Requires robust traceability and industrial partnerships
Australia	Hydrogen Guarantee of Origin	Certification based on primary energy source	Reinforces need for integration with renewables
Benelux	EU Integrated Certification	Common environmental and market criteria	Requires multilevel political and regulatory dialogue

Source: Abad, & Dodds (2020); Veum et al. (2019); Evangelista et al. (2023); Gabrielli, & Tokarski (2024); ARENA (2021); Wurster, & Hof (2021); CERTIFHY (2022); IRENA (2024).

Thus, the development of a regulatory framework for hydrogen certification in Brazil must necessarily involve a critical analysis of international experiences and a solid institutional articulation. Hinicio (2021) emphasizes that the most effective mechanisms combine stringent technical criteria with well-defined economic incentives, aiming to engage the private sector and ensure reliability at the international level. According to Vallejos-Romero et al. (2022), certification should not be limited to technical and environmental issues but must also include social and regional criteria, thereby guaranteeing an equitable and inclusive energy transition. In this way, Brazil will be able not only to adapt to global demands but also to influence emerging standards in a rapidly consolidating market.

IV. DISCUSSION AND CONCLUSION

The present research fully achieved the initially established objectives by conducting a critical, comprehensive, and up-to-date analysis of the technological pathways for hydrogen production in Brazil, emphasizing the economic and regulatory aspects involved. Through a rigorous investigative effort, grounded in a systematic literature review and the careful selection of technical-scientific data, it was possible to compile and structure information into three analytical tables that clearly and objectively synthesize the main aspects of the topic discussed. The organization of this information constitutes a significant contribution to academic discourse and the formulation of public policies aimed at the sustainable development of the hydrogen value chain.

Table 1 below summarizes the technological pathways for hydrogen production, highlighting their main characteristics, maturity levels, and applicability within the Brazilian context. Table 2 — Economic Comparison of the Main Hydrogen Production Pathways in Brazil — provides a detailed analysis of costs, economic viability, and available incentives, offering support for strategic investment decisions in the sector. Table 3 — Environmental Impacts of Green Hydrogen Production by Electrolysis: Waste, Critical Aspects, and Key References — addresses the environmental implications associated with these pathways, emphasizing key challenges and relevant literature. Finally, Table 4 — Hydrogen Certification Standards: International Comparison and Implications for Brazil — examines the technical and environmental criteria required by international certifications, underscoring their repercussions for the Brazilian market and competitiveness in the global low-carbon hydrogen trade.

The research also demonstrated that the implementation of a hydrogen-based economy in Brazil requires joint initiatives between the public and private sectors, as well as the development of regulatory guidelines that ensure predictability and legal certainty. The establishment of a cleaner and more resilient energy matrix is primarily conditioned on the articulation among technological innovation, financial incentives, and strategies for international market integration—elements extensively analyzed throughout this study. Based on the compiled graphs, it is evident that the country holds considerable comparative advantages, especially regarding the abundant availability of renewable energy sources; however, it lacks a solid regulatory framework aligned with international standards.

Given the identified gaps, it is suggested that future research delve more deeply into the effects of specific public policies on the viability of hydrogen production pathways across different regions of the country, as well as assess international market acceptance of certified Brazilian hydrogen. Furthermore, examining the role of universities and research centers in technological innovation aimed at decarbonizing production processes would be valuable. Empirical analyses and economic simulations of future scenarios could deepen the understanding of Brazil's strategic integration into the global hydrogen economy, fostering scientific progress and enhancing the country's energy sovereignty.

REFERENCES

[1] Abad, A. V., & Dodds, P. E. (2020). Green hydrogen characterisation initiatives: Definitions, standards, guarantees of origin, and challenges. *Energy Policy, 138*, 111300. https://doi.org/10.1016/j.enpol.2019.111300

[2] Al-Qahtani, A., Elkamel, A., Douglas, P. L., & Croiset, E. (2021). Environmental impacts of hydrogen production routes by life cycle analysis. *Environmental Chemistry Letters, 19*(5), 3607–3622. https://doi.org/10.1007/s10311-021-01245-8

[3] ANEEL – Brazilian Electricity Regulatory Agency. (2024, March). *Strategic Project: Hydrogen in the Context of the Brazilian Electric Sector*. Brasília: ANEEL. Available at: https://www2.aneel.gov.br/cedoc/adsp2024778_2.pdf. Accessed: June 2025.

[4] ARENA – Australian Renewable Energy Agency. (2021). *General Funding Strategy, 2021/22 – 2023/24*. Available at: https://arena.gov.au/assets/2021/09/2021-22-to-2023-24-arena-general-funding--strategy.pdf. Accessed: June 2025.

[5] Bareiß, K., de la Rua, C., Möckl, M., & Hamacher, T. (2022). Life cycle assessment of green hydrogen production through electrolysis: A literature review. *Journal of Cleaner Production, 340*, 130145. https://doi.org/10.1016/j.jclepro.2022.130145

[6] Bonnet-Cantalloube, B., Engel, H., Verhoeven, A., & Hydrogen Europe. (2023, March). *Clean ammonia in the future energy system*. Brussels: Hydrogen Europe. Available at: https://hydrogeneurope.eu/wp-content/uploads/2023/03/2023.03_H2Europe_Clean_Ammonia_Report_DIGITAL_FINAL.pdf. Accessed: June 2025.

[7] Brazil. Ministry of Mines and Energy (MME). (2021b). *Energy Research Company. Foundations for the Consolidation of the Brazilian Hydrogen Strategy: Technical Note*. Brasília. Available at: https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-569/Hidrogênio_23Fev2021NT%20%282%29.pdf. Accessed: June 14, 2025.

[8] Brazil. Ministry of Mines and Energy (MME). (2021a). *National Hydrogen Program: Proposal for Guidelines*. Brasília. Available at: https://www.gov.br/mme/pt-br/assuntos/noticias/mme-apresenta-ao-cnpe-proposta-de-diretrizes-para-o-programa-nacional-do-hidrogenio-pnh2/HidrognioRelatriodiretrizes.pdf. Accessed: June 15, 2025.

[9] Brazil. Ministry of Mines and Energy (MME). (2023). *National Hydrogen Program: Triennial Work Plan 2023–2025*. Brasília. Available at: https://www.gov.br/mme/pt-br/assuntos/noticias/PlanodeTrabalhoTrienalPNH2.pdf. Accessed: June 15, 2025.

[10] Bristowe, G., & Smallbone, A. (2021). The key techno-economic and manufacturing drivers for reducing the cost of power-to-gas and a hydrogen-enabled energy system. *Hydrogen, 2*(3), 273–300. https://doi.org/10.3390/hydrogen2030015

[11] Cellard, A. (2019). *Document analysis in qualitative research*. São Paulo: UNESP.

[12] CertifHy. (2022). *CertifHy Scheme*. Available at: http://www.certifhy.eu/. Accessed: June 2025.

[13] Chatterjee, S., & Mohan, S. V. (2021). Simultaneous production of green hydrogen and bioethanol from segregated sugarcane bagasse hydrolysate streams with circular biorefinery design. *Chemical Engineering Journal, 425*, 130386. https://doi.org/10.1016/j.cej.2021.130386

[14] CNI – National Confederation of Industry. (2022). *Sustainable Hydrogen – Perspectives and Potential for Brazilian Industry*. Available at: https://static.portaldaindustria.com.br/portaldaindustria/noticias/media/filer_public/b4/73/b47388bd-e740-4df1-80a9-9b8ecbf9720f/estudo_hidrogenio_sustentavel.pdf. Accessed: June 2025.

[15] Dawood, F., Anda, M., & Shafiullah, G. M. (2020). Hydrogen production for energy: An overview. *International Journal of Hydrogen Energy, 45*(7), 3847–3869. https://doi.org/10.1016/j.ijhydene.2019.12.059

[16] Derwent, R., Simmonds, P., O'Doherty, S., Ryall, D., & Stevenson, D. (2006). Global environmental impacts of the hydrogen economy. *International Journal of Nuclear Hydrogen Production and Applications, 1*(1), 57–67. https://doi.org/10.1504/IJNHPA.2006.009869

[17] Espitalier-Noël, M., Bonnet-Cantalloube, B., & Hydrogen Europe. (2023). *Clean Hydrogen Monitor 2024*. Brussels: Hydrogen Europe. Available at: https://hydrogeneurope.eu/wp-content/uploads/2023/10/Clean_Hydrogen_Monitor_11-2023_DIGITAL.pdf. Accessed: June 2025.

[18] Evangelista, E., Magalhães, G., & Mariani, R. (2023). *Green hydrogen: Legal, regulatory, and technical perspectives*. Rio de Janeiro: Synergia.

[19] Fussuma, T. M. D., Gimenes, A. L. V., Udaeta, M. E. M., & Nascimento, V. T. (2024). Analysis of the potential for production and export of green hydrogen in the Brazilian Northeast. In *Proceedings of the Brazilian Solar Energy Congress – CBENS*. https://doi.org/10.59627/cbens.2024.2475

[20] Gabrielli, J. S., & Tokarski, A. P. R. (2024). Regulatory studies for green hydrogen certification in Brazil: Energy transition. *Princípios, 43*(170), 93–114. https://doi.org/10.14295/principios.2675-6609.2024.170.005

[21] Gilles, F., & Brzezicka, P. (2022). *Unlocking the hydrogen economy – Stimulating investment across the hydrogen value chain: Investor perspectives on risks, challenges and the role of the public sector*. European Investment Bank.

[22] Hinicio. (2021). *Deliverable 2: Benchmark of international practices on low-carbon and green H2 certification mechanisms*. Available at: https://energia.gob.cl/sites/default/files/documentos/green_hydrogen_certification_-_international_benchmark.pdf. Accessed: June 2025.

[23] Hinicio, ABL, & GME. (2023). *Technical support to accelerate green hydrogen development in Brazil. A1.T2: Brazil's role in the international value chain for LCH – Export markets and port potential*. Brussels: Hinicio; ABL; GME.

[24] IEA – International Energy Agency. (2024). *Global Hydrogen Review 2024*. Paris: IEA. Available at: https://www.iea.org/reports/global-hydrogen-review-2024. Accessed: June 2025.

[25] IEA – International Energy Agency. (2023). *Renewables 2023: Analysis and forecast to 2028*. Paris: IEA. Available at: https://iea.blob.core.windows.net/assets/96d66a8b-d502-476b-ba94-54ffda84cf72/Renewables_2023.pdf. Accessed: June 2025.

[26] IRENA – International Renewable Energy Agency. (2020). *Green hydrogen: Electrolysis, ammonia and other e-fuels*. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Green_Hydrogen_breakthrough_2021.pdf?la=en&hash=40FA5B8AD7AB1666EECBDE30EF458C45EE5A0AA6. Accessed: June 2025.

[27] RENA – International Renewable Energy Agency. (2024). *Green hydrogen derivatives: Trends in regulation, standardisation and certification*. Abu Dhabi.

[28] Jenkins, B., Squires, D., Barton, J., Strickland, D., Wijayantha, K. G. U., Carroll, J., Wilson, J., Brenton, M., & Thomson, M. (2022). Techno-economic analysis of low carbon hydrogen production from offshore wind using Battolyser technology. *Energies, 15*, 5796.

[29] Ji, M., & Wang, J. (2021). Review and comparison of various hydrogen production methods based on costs and life cycle impact assessment indicators. *International Journal of Hydrogen Energy, 46*(78), 38612–38635. https://doi.org/10.1016/j.ijhydene.2021.09.142

[30] Kant, S. B., Singh, R. S., Agrawal, R., & Kumar, A. (2021). Renewable biohydrogen production from lignocellulosic biomass using fermentation and integration of systems with other energy generation technologies. *Science of the Total Environment, 765*, 144429. https://doi.org/10.1016/j.scitotenv.2020.144429

[31] Lee, B., Lee, K., Lee, D., & Lim, H. (2021). Integrative techno-economic and environmental assessment for green H_2 production by alkaline water electrolysis based on experimental data. *International Journal of Hydrogen Energy, 46*(29), 15432–15445. https://doi.org/10.1016/j.ijhydene.2021.02.135

[32] Li, Y., Liu, C., Li, X., & Zhang, Y. (2021). Quantification of freshwater consumption and scarcity footprints of hydrogen from water electrolysis: A methodology framework. *Journal of Cleaner Production, 297*, 126140. https://doi.org/10.1016/j.jclepro.2021.126140

[33] Mehmeti, A., Angelis-Dimakis, A., & Bauen, A. (2024). Life cycle environmental impacts and costs of water electrolysis technologies for green hydrogen production in the future. *Energy, Sustainability and Society, 14*(1), 1–17. https://doi.org/10.1186/s13705-024-00465-5

[34] MME – Ministry of Mines and Energy. (2021). *H2Brasil – Expansion of Green Hydrogen*. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. Available at: https://www.gov.br/mme/pt-br/assuntos/secretarias/spe/h2-brasil. Accessed: June 16, 2025.

[35] Oliveira, R. C. de. (2022). *Overview of Hydrogen in Brazil*. Discussion Paper No. 2787. Institute for Applied Economic Research (IPEA), Brasília. Available at: https://repositorio.ipea.gov.br/bitstream/11058/11291/1/td_2787_web.pdf. Accessed: June 15, 2025.

[36] Palmer, G., Middleton, P., & Taylor, M. (2022). Large-scale hydrogen production via water electrolysis: A techno-economic and environmental assessment. *Energy & Environmental Science, 15*(8), 3210–3225. https://doi.org/10.1039/D2EE01023B

[37] Pizzani, L., Silva, R., Bello, S., & Hayashi, M. (2012). The art of bibliographic research in the pursuit of knowledge. *RDBCI – Revista Digital de Biblioteconomia e Ciência da Informação, 10*(1), 53–66.

[38] Quitzow, R., Wappelhorst, S., Obergassel, W., & Thielges, S. (2023). *Mobilizing Europe's full hydrogen potential: Entry-points for action by the EU and its member states* (Hypat Discussion Paper No. 5). Karlsruhe: Fraunhofer ISI. Available at: https://publica-rest.fraunhofer.de/server/api/core/bitstreams/6eb07f2f-f7c9-42dc-8b8c-41f09b415eab/content. Accessed: June 16, 2025.

[39] Ribeiro Filho, J. R., Tahim, E. F., & Veras, V. M. V. (2023). Perspectives for green hydrogen: An analysis in light of the Triple Helix model. *Brazilian Journal of Development, 9*(1), 1531–1553. https://doi.org/10.34117/bjdv9n1-106

[40] Sherif, S. A., Khalil, A., Al-Sulaiman, F. A., & Kamil, M. (2023). Recent and future advances in water electrolysis for green hydrogen generation: Critical analysis and perspectives. *Sustainability, 16*(1), 1–25. https://doi.org/10.3390/su16010001

[41] Siffert, N., & Rocha, K. (2025). *The low-carbon hydrogen market in Brazil: Perspectives and challenges until 2030* (Discussion Paper No. 3082). Brasília, DF: Institute for Applied Economic Research (Ipea). https://dx.doi.org/10.38116/td3082-port

[42] Vallejos-Romero, A., Cordoves-Sánchez, M., Cisternas, C., Sáezardura, F., Rodríguez, I., Aledo, A., Boso, Á., Prades, J., & Álvarez, B. (2022). Green hydrogen and social sciences: Issues, problems, and future challenges. *Sustainability, 15*(1), 303. https://doi.org/10.3390/su15010303

[43] Valles, M. S. (2007). *Qualitative research techniques in social sciences: Methodological reflection and professional practice*. Madrid: Síntesis.

[44] Veum, K. C., Samadi, S., & Resch, G. (2019). *Taking CertifHy to the next level: Roadmap for building a dual hydrogen certification infrastructure for guarantees of origin and for certification of renewable hydrogen in transport*.

[45] Wurster, R., & Hof, E. (2021). The German hydrogen regulation, codes and standards roadmap. *International Journal of Energy Research, 45*(4), 4835–4840.

[46] Yu, M., Wang, K., & Vredenburg, H. (2021). Insights into low-carbon hydrogen production methods: Green, blue, and aqua hydrogen. *International Journal of Hydrogen Energy, 46*(41), 21261–21273. https://doi.org/10.1016/j.ijhydene.2021.04.016

.