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TECHNOLOGICAL PRIORITIZATION IN THE GREEN HYDROGEN VALUE CHAIN IN CEARÁ: EMERGING TRENDS AND SCIENTIFIC AND TECHNOLOGICAL DEVELOPMENT POTENTIAL

PRIORIZAÇÃO TECNOLÓGICA NA CADEIA DO HIDROGÊNIO VERDE NO CEARÁ: TENDÊNCIAS EMERGENTES E POTENCIAL DE DESENVOLVIMENTO CIENTÍFICO E TECNOLÓGICO

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Ana Karen Silveira Pereira Caracas[1]

Ana Verucia Leitão da Silva Vasconcelos[2]

Constantino Frate Junior[3]

Esaú Aguiar Carvalho[4]

Francisco Fabio Braga Florêncio[5]

Francisco Jeandson Rodrigues da Silva[6]

Francisco José da Silva Fonteles[7]

Francisco José Lopes Cajado[8]

Givanildo Ximenes Santana[9]

Irene Mendes Fontes[10]

Isaac Taumaturgo Pinto[11]

José Nabuco Ribamar Neto[12]

Paulo Henrique Barbosa Sousa[13]

Rickardo Léo Ramos Gomes[14]

Roberto Augusto Caracas Neto[15]

Tadeu Dote Sá[16]

Yuri Falcão da Silva[17]

ABSTRACT

The energy transition and the expansion of renewable energy sources have increased scientific and technological attention to green hydrogen, particularly given its integration into different industrial and energy sectors. In this context, structuring its value chain requires an integrated analysis of the technologies involved and their suitability to the energy, industrial, and innovation conditions of each territory, including Ceará. The general objective is to analyze and prioritize emerging technologies associated with the green hydrogen value chain that have the greatest relevance and potential for scientific and technological development in Ceará, considering the perceptions of specialists and the specific characteristics of the state's energy, industrial, and innovation context. The research is characterized as qualitative and exploratory, employing a bibliographic review and documentary research as its methodological procedures. The bibliographic review compiled national and international scientific publications related to the subject, while the documentary research examined technical and institutional documents concerning hydrogen and Brazil's and Ceará's energy conditions, integrating different information bases to support the technological analysis and prioritization. In summary, the research demonstrated that technological prioritization within Ceará's green hydrogen value chain should consider the articulation among innovation, technological maturity, infrastructure, industrial applications, market conditions, knowledge, sustainability, regulation, and the energy transition. The study achieved its proposed objectives by identifying technologies, analyzing their evaluation criteria, and structuring a prioritization approach based on specialists' perceptions, thereby contributing to broadening the scientific basis for discussions on the technological development of green hydrogen in the state.

Keywords: Green hydrogen; Emerging technologies; Innovation; Energy transition.

RESUMO

A transição energética e a expansão das fontes renováveis têm ampliado a atenção científica e tecnológica direcionada ao hidrogênio verde, especialmente diante de sua inserção em diferentes segmentos industriais e energéticos. Nesse contexto, a estruturação de sua cadeia de valor demanda a análise integrada das tecnologias envolvidas e de sua adequação às condições energéticas, industriais e de inovação de cada território, incluindo o Ceará. O objetivo geral consiste em analisar e priorizar as tecnologias emergentes associadas à cadeia do hidrogênio verde com maior relevância e potencial de desenvolvimento científico e tecnológico no Ceará, considerando a percepção de especialistas e as especificidades do contexto energético, industrial e de inovação do estado. A pesquisa caracteriza-se como qualitativa e exploratória, tendo como procedimentos a revisão bibliográfica e a pesquisa documental. A revisão bibliográfica reuniu produções científicas nacionais e internacionais relacionadas ao tema, enquanto a pesquisa documental examinou documentos técnicos e institucionais referentes ao hidrogênio e às condições energéticas brasileiras e cearenses, articulando diferentes bases de informação para subsidiar a análise e a priorização tecnológica. Em síntese, a pesquisa demonstrou que a priorização tecnológica da cadeia do hidrogênio verde no Ceará deve considerar a articulação entre inovação, maturidade tecnológica, infraestrutura, aplicação industrial, mercado, conhecimento, sustentabilidade, regulação e transição energética. O estudo alcançou os objetivos propostos ao identificar tecnologias, analisar seus critérios de avaliação e estruturar uma abordagem de priorização baseada na percepção de

especialistas, contribuindo para ampliar a base científica de discussão sobre o desenvolvimento tecnológico do hidrogênio verde no estado.

Palavras-chave: Hidrogênio verde; Tecnologias emergentes; Inovação; Transição energética.

1. INTRODUCTION

The current energy transition has attracted scientific, technological, and industrial attention to energy vectors that can contribute to reducing emissions generated by production systems and diversifying energy matrices. In this context, green hydrogen has gained prominence due to its ability to connect renewable electricity sources with a wide range of industrial and energy sectors. The value chain associated with this energy vector encompasses a diverse set of technologies, ranging from production, purification, storage, transportation, distribution, and utilization. Consequently, its development depends on integrated technological decisions and on the specific characteristics of each territory.

In Ceará, the debate surrounding the green hydrogen value chain is intrinsically associated with renewable energy resources and the configuration of the state's energy matrix, the abundance of natural resources, transformations in its industrial structure, and institutional initiatives aimed at consolidating a low-carbon economy. Documents such as the *MasterPlan Hidrogênio Verde Ceará* (FIEC, 2024), the study by the International Energy Agency (2021), the IPEA study (2022), and *Ceará: Atlas Eólico e Solar* (Ceará, 2019) indicate the need to integrate energy resources, infrastructure, innovation, planning, and productive arrangements. From this perspective, technological prioritization constitutes a relevant scientific issue, enabling greater emphasis on emerging technologies that are more closely aligned with the state's energy, industrial, and innovation contexts. Accordingly, the investigation was guided by the following research question: Which emerging technologies in the green hydrogen value chain stand out and have greater potential for scientific and technological development in Ceará, according to specialists?

The general objective is to analyze and prioritize emerging technologies associated with the green hydrogen value chain that have the greatest relevance and potential for scientific and technological development in Ceará, considering specialists' perceptions and the specific characteristics of the state's energy, industrial, and innovation context. To achieve this objective, the following specific objectives were established: 1. To identify the main emerging technologies that comprise the green hydrogen value chain, considering the different stages of production, storage, transportation, distribution, and utilization; 2. To characterize the energy, industrial, logistics, scientific, technological, and institutional conditions that position Ceará as a strategic territory for the development of the green hydrogen value chain. 3. To analyze the relevance and potential for scientific and technological development of emerging technologies related to green hydrogen in the context of Ceará, considering their opportunities for innovation, industrial application, and contribution to the energy transition; 4. To prioritize the emerging technologies in the green hydrogen value chain with the greatest potential for scientific and technological development in Ceará, based on specialists' perceptions and criteria related to technological relevance, maturity, innovation, and application prospects.

The research is characterized as qualitative and exploratory, employing a bibliographic review and documentary research as methodological procedures. The bibliographic review covered national and international scientific publications related to the subject, while the documentary research analyzed technical and institutional documents concerning hydrogen and the energy conditions of Brazil and Ceará. This approach enabled the integration of scientific knowledge and contextual information to support the analysis and technological prioritization.

The article is organized into four sections, in addition to this Introduction. The first presents the Introduction, providing the contextualization of the topic, the research question, and the objectives. The second presents the Methodology, addressing the approach and procedures employed. The third develops the Theoretical Framework, structured into three topics addressing emerging technologies, the relationship between green hydrogen, innovation, and scientific and technological development in Ceará, and technological prioritization. Finally, the fourth section presents the Final Considerations, which synthesize the main results, the contributions of the study, and possibilities for future research.

2. THEORETICAL FRAMEWORK

The theoretical framework was organized into three interconnected topics to establish an analytical sequence consistent with the research problem and objectives. The first topic addresses emerging technologies and the green hydrogen value chain, encompassing the different stages, technological pathways, and applications associated with this energy vector. The second topic discusses green hydrogen, innovation, and scientific and technological development in Ceará, considering the state's energy, industrial, institutional, and territorial characteristics. Finally, the third topic addresses technological prioritization and the assessment of emerging trends in the green hydrogen value chain, focusing on the criteria and dimensions used to analyze and establish priorities among technologies related to the sector.

2.1. Emerging Technologies And The Green Hydrogen Value Chain

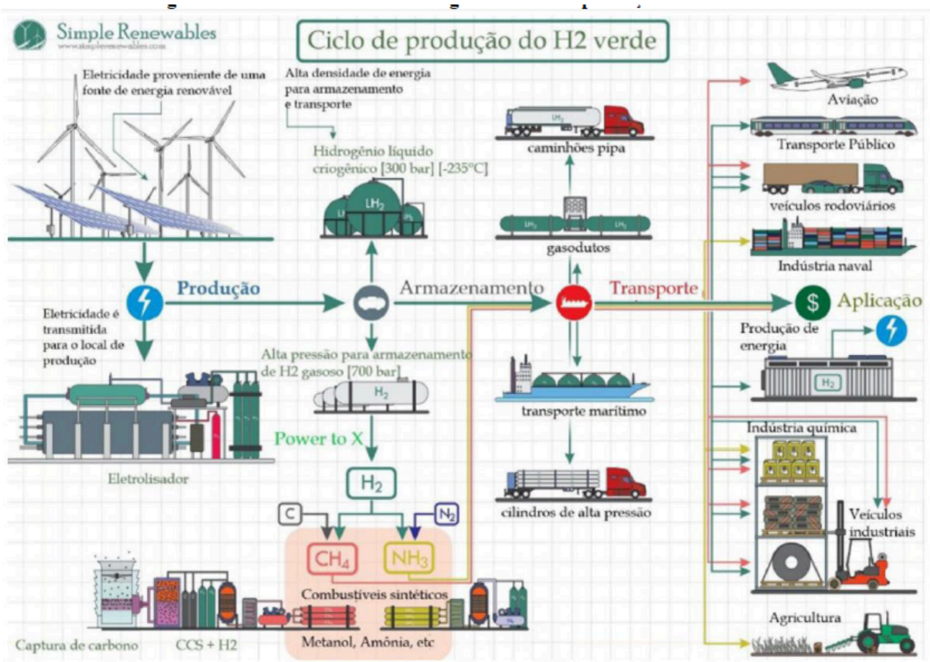
Green hydrogen is a key component of the current transformation of energy systems, as it connects electricity from renewable sources with industrial processes and diverse forms of energy consumption. Its relevance extends beyond gas production to the development of a technological value chain encompassing renewable generation, electrolysis, conditioning, storage, transportation, distribution, and end uses. According to Nóbrega et al. (2022), hydrogen production from renewable sources involves several technological pathways whose development is associated with the expansion of renewable energy and the search for lower-carbon alternatives.

The green hydrogen value chain needs to be understood systemically because technological choices at one stage affect the others. Production, storage, transportation, and utilization are interdependent within the emerging hydrogen economy, as demonstrated by De Castro et al. (2023). Therefore, the competitiveness of a technology cannot be assessed solely on the basis of its individual performance, but also according to its capacity to integrate with the energy, industrial, and logistics infrastructures required for hydrogen transportation.

Production represents the first link in this chain, with water electrolysis constituting one of the main pathways for hydrogen generation from renewable electricity. Electrolyzers therefore represent an important technological component, while different configurations and possibilities for integration with wind and solar generation expand the options for organizing production systems. According to Mueller and François (2023), the expansion of green hydrogen is associated with the availability of renewable resources and the need to develop solutions that integrate energy generation, hydrogen production, and its utilization across different economic sectors.

Figure 1 - illustrates the integration of the value chain as a whole, from renewable electricity generation and electrolysis-based production to storage, transportation, and final utilization. The figure highlights several conditioning and utilization options, including liquid hydrogen, pressurized storage, pipeline transportation, maritime and road transportation, and applications in industry, mobility, power generation, and agriculture. This representation helps delimit the technological stages considered in the identification of emerging technologies in this study.

Figure 1. Green hydrogen value chain from production to final utilization



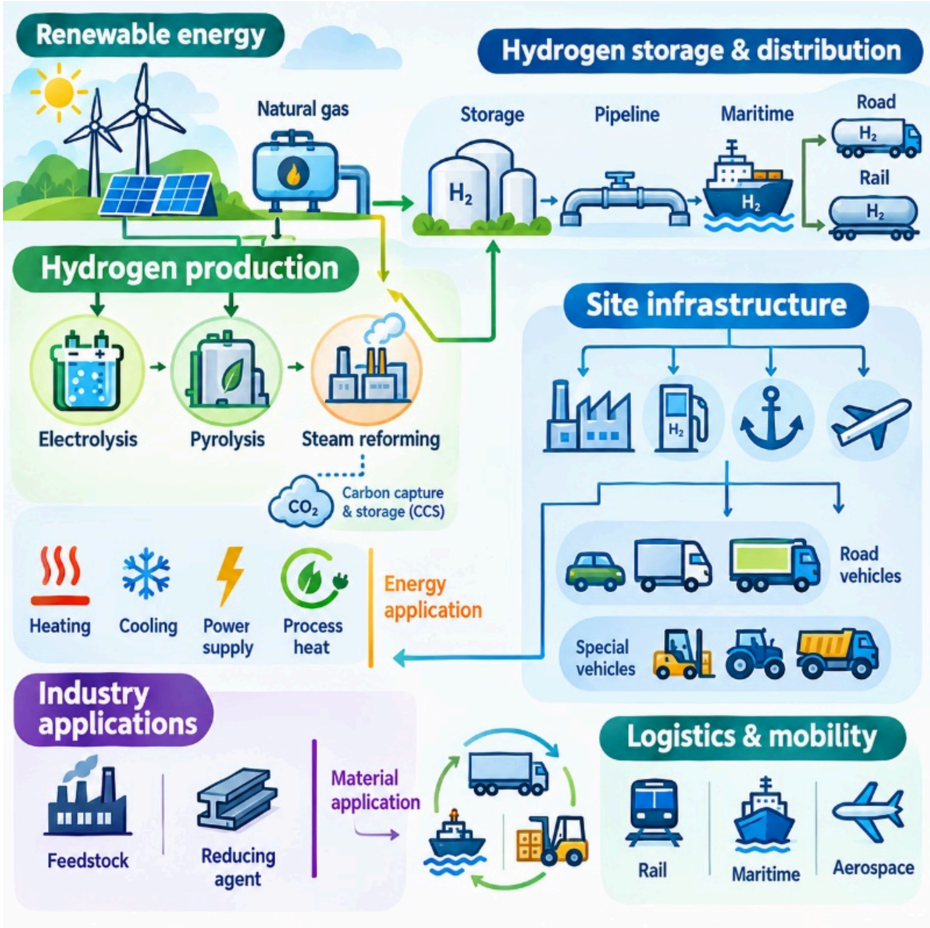
Source: Castro et al. (2023)

Storage represents another important link in the value chain, particularly because the physicochemical properties of hydrogen require specific conditions for its storage and transportation. Among the various options available within the chain are high-pressure storage and cryogenic liquid storage, as well as alternatives involving the conversion of hydrogen into other energy carriers. According to Garcia-Navarro et al. (2023), transforming the value chain requires an integrated set of storage, distribution, and transportation solutions that account for the specific characteristics of each application and the existing infrastructure conditions.

In Ceará, this differentiation among value chain links is already evident in practice. While electrolysis-based production is advancing toward commercial scale through contracted plants, the storage link already has a defined technological pathway at the Pecém Complex, with the selection of an operator for the hub's green ammonia terminal (Complexo do Pecém, 2026c). This situation illustrates how different links in the value chain can exhibit distinct levels of technological maturity and definition within the same territory, reinforcing the need for a prioritization instrument capable of addressing each link individually rather than treating the value chain as a single block, according to specific criteria related to maturity, infrastructure, and productive linkages.

Transportation, in turn, adds another layer of technological complexity to the value chain, as it encompasses different modes and operating conditions. Options for transporting hydrogen and its derivatives include pipelines, maritime transportation, high-pressure cylinders, and road transportation. Figure 2 also contributes to this understanding by presenting an integrated representation of technologies for production, storage, distribution, local infrastructure, industrial applications, and mobility, reinforcing that the development of hydrogen cannot occur independently across these different technological systems.

Figure 2. Technological integration of hydrogen production, storage, distribution, and applications



Source: Illustrative representation of the hydrogen technological value chain based on Garcia-Navarro et al. (2023).

In Brazil, the structure of this value chain depends on the territorial, energy, regulatory, and industrial conditions of each location. The International Energy Agency (2021) identifies opportunities for hydrogen development in Latin America based on the availability of renewable resources and integration into national and international markets. The IPEA (2022) points to opportunities for Brazil associated with the energy transition and industrial development, as well as the creation of new productive chains, while also identifying challenges related to infrastructure, investment, and the consolidation of the regulatory environment.

In Ceará, this topic assumes specific characteristics when considering the integration of renewable energy sources, the industrial sector, port infrastructure, and efforts to establish a green hydrogen ecosystem. The *Master Plan Hidrogênio Verde Ceará* provides guidelines for structuring this value chain in the state. In parallel, Benvindo (2024) investigates how the Ceará Green Hydrogen Hub fits into the global energy transition, considering interactions among different actors and institutions. Moraes et al. (2026) also discuss the possibility of incorporating green hydrogen into Ceará's energy matrix, helping to contextualize the subject within the state.

Therefore, the identification of technologies to be evaluated by specialists must incorporate criteria that go beyond their existence or level of technological development and also consider how these technologies relate to Ceará's scientific and technological development conditions. According to Ronceros et al. (2025), technical and regulatory factors are fundamental to establishing green hydrogen in Brazil. Complementarily, FIEC (2024) addresses the organization of the industrial, technological, and institutional capacities required to strengthen the value chain in Ceará. Lameiras (2019, p. 82), in turn, argues:

> *[...] even though Brazil already has a well-structured ecological matrix, it is important for the country to go beyond introducing hydrogen into its energy matrix and instead build the conditions to become a major player in this new market, particularly as a major supplier of green hydrogen.*

From this perspective, technological prioritization must be capable of considering different aspects that enable specialists to conduct a comparative assessment of the identified options. Preventing the assessment from being reduced to a single indicator is the purpose of a categorical selection encompassing technological relevance, maturity, innovation potential, industrial applicability, infrastructure, scientific and technological development, value chain integration, and contribution to the energy transition. In defining green hydrogen, Fonseca (2020, p. 42) establishes a direct connection with sustainable development:

> *In practical terms, green hydrogen is the new guarantor of Sustainable Development because, while meeting current needs through global economic development, it is capable of preserving the needs of future generations through a clean planet free from climatic extremes.*

The notion of technological maturity employed here is associated with the *Technology Readiness Level* (TRL) scale, originally developed by NASA to assess the maturity of technologies across nine levels, ranging from the observation of basic principles to operational demonstration in a real environment (Mankins, 1995). The scale was subsequently adopted by funding agencies and the energy industry as a common framework for comparing technological pathways within the same productive chain. This scale is connected to the technological *roadmapping* approach, understood as a planning instrument that relates market needs, available technologies, and future development trajectories (Phaal; Farrukh; Probert, 2004), providing a theoretical basis for the premise that prioritizing technologies within an emerging value chain constitutes a legitimate stage of innovation management rather than an arbitrary choice. From this multidimensional perspective, the categories and criteria that may comprise the assessment instrument to be applied to specialists are outlined in Table 1.

Table 1. Categories and criteria for prioritizing emerging technologies in the green hydrogen value chain in Ceará

Assessment category	Criterion for assessment by specialists	Guiding question for the specialist
Technological relevance	Importance of the technology for the development of the green hydrogen value chain	What is the degree of relevance of this technology to the consolidation of the green hydrogen value chain in Ceará?
Technological maturity	Degree of development and availability of the technology for real-world applications	To what extent does the technology present a level of development compatible with its application?
Technological innovation	Capacity to stimulate new products, processes, and technological solutions	To what extent can the technology stimulate innovation processes in the state?
Industrial applicability	Possibility of use in existing or expanding industrial activities	What is the degree of applicability of the technology to industrial activities related to hydrogen?
Infrastructure	Compatibility with energy, industrial, port, and logistics infrastructure	To what extent does the infrastructure available or planned in Ceará facilitate the adoption of the technology?
Scientific and technological development	Capacity to stimulate research, skills development, and knowledge production	What is the contribution of the technology to scientific and technological development in Ceará?
Integration into the value chain	Capacity to articulate with other stages of production, storage,	To what extent does the technology foster

	transportation, and utilization	integration among different links in the value chain?
Energy transition and decarbonizatio n	Contribution to replacing higher-emission sources or processes	What is the contribution of the technology to the energy transition and emissions reduction?
Integration into markets and applications	Possibility of use across different sectors and productive chains	To what extent does the technology present conditions for application in markets and sectors related to hydrogen?

Source: Prepared by the authors based on Nóbrega et al. (2022), De Castro et al. (2023), International Energy Agency (2021), Garcia-Navarro et al. (2023), IPEA (2022), FIEC (2024), Benvindo (2024), Ronceros et al. (2025), Moraes et al. (2026), and Mueller and François (2023).

These categories are intended to enable the conversion of specialists' perceptions into comparable data without losing the multidimensional nature of technological prioritization. The proposal suggests that a technology may be highly relevant from a scientific perspective but face limitations in terms of infrastructure or maturity, whereas another may be more applicable in the short term but make a smaller contribution to knowledge generation. Thus, the joint assessment of the criteria makes it possible to establish a hierarchy of emerging technologies that are most closely aligned with Ceará's scientific, technological, industrial, and energy development conditions.

2.2. Ceará as a Strategic Territory For Green Hydrogen Development

Ceará presents conditions that favor its strategic integration into the green hydrogen value chain, particularly due to the availability of renewable resources, its wind and solar power generation conditions, and the articulation among energy, industrial, and logistics infrastructure. *Ceará: Atlas Eólico e Solar* (Ceará, 2019) provides an important reference for understanding these conditions, while Almeida et al. (2025) highlight state-specific characteristics related to the use of green hydrogen as an alternative for transforming the energy matrix. In this context, the availability of renewable energy sources constitutes one of the foundations for structuring production systems associated with electrolysis and for integrating energy generation with hydrogen production.

Ceará's strategic position is also related to the existence of the Pecém Industrial and Port Complex, the Export Processing Zone, and its connectivity with national and international markets. Studies and institutional documents addressing green hydrogen in the state highlight the integration of production, storage, transportation, and export as relevant elements for consolidating the value chain. From this perspective, the existing infrastructure helps bring energy production closer to industrial and logistics activities, an aspect that De Castro et al. (2023) identify as relevant to structuring the hydrogen economy.

Another distinctive element is the development of a specific institutional strategy for the sector. On February 19, 2021, the Government of the State of Ceará created the country's first Green Hydrogen Hub, an initiative associated with attracting investments and establishing a productive chain linked to renewable energy sources (Bezerra, 2021). The initiative was accompanied by coordination among the State Government, the Federation of

Industries of the State of Ceará, the Federal University of Ceará, and the Pecém Complex, strengthening the connection among public authorities, the productive sector, and science, technology, and innovation institutions. The *MasterPlan Hidrogênio Verde Ceará* (FIEC, 2024) expands this perspective by establishing guidelines for structuring the value chain and integrating it into the state's industrial development strategies.

The scientific and technological dimension constitutes another component of Ceará's strategy. The Federal University of Ceará and other educational and research institutions have been developing studies and initiatives related to the production, storage, transportation, utilization, and other stages of the green hydrogen value chain. The establishment of research networks and the coordination among universities, science and technology institutions, and companies contribute to bringing knowledge production closer to industrial demands. In this regard, Barbosa et al. (2025) emphasize the importance of professional training and public policies for consolidating the sector, while Gomes et al. (2025) highlight the need to consider technological, economic, regulatory, and certification aspects across the different hydrogen production and utilization pathways.

The prospect of developing new industrial value chains also reinforces Ceará's strategic position. Rocha and Pompeu (2024) associate low-carbon hydrogen with the process of green neoindustrialization in the state, while Feitosa Neto et al. (2026) link *powershoring*, innovation, and decarbonization to the emergence of new industrial value chains within Brazil's economic geography. Schneider, Santos, and Arbache (2026), in turn, discuss *powershoring* as a development strategy for the Northeast, a perspective that makes it possible to relate the availability of renewable energy to opportunities for attracting and reorganizing industrial activities. Thus, green hydrogen can be understood not only as an energy vector but also as an element that connects renewable energy, innovation, industrialization, and technological development.

However, these advantages do not eliminate the challenges associated with consolidating this value chain. The expansion of green hydrogen requires investments, adequate infrastructure, skills development, regulatory certainty, certification, and assessment of territorial and environmental impacts. Ribeiro and Matos (2025) highlight opportunities for export integration and infrastructure and regulatory challenges, while Queiroz and Monteiro Júnior (2026) draw attention to regulatory aspects related to water resources in the Ceará context. Caiafa, Romijn, and De Coninck (2025) also demonstrate the need to consider the opportunities, risks, synergies, and conflicts associated with the development of partnerships around green hydrogen. Therefore, Ceará's favorable conditions support its strategic position while also reinforcing the need to prioritize technologies compatible with its energy, industrial, environmental, and institutional characteristics.

2.3. Green Hydrogen, Innovation, And Scientific And Technological Development Potential In Ceará

The expansion of green hydrogen in Ceará should be understood within the context of the energy transition and the transformation of the technological, industrial, and institutional foundations associated with energy production and use. In this context, innovation is not limited to the equipment employed in hydrogen production but also encompasses infrastructure, processes, skills, business models, regulation, and coordination among different stakeholders. Barbosa et al. (2025) emphasize that Brazil has favorable conditions for structuring this value chain, although challenges related to costs, infrastructure, professional training, and regulation persist.

In Ceará, the availability of renewable resources constitutes one of the material foundations for the expansion of this new productive chain. Ceará's *Atlas Eólico e Solar* records the conditions for exploiting these energy sources throughout the state, while Almeida et al. (2025) relate the state's climatic, geographical, scientific, and investment characteristics to the development of initiatives focused on green hydrogen. The combination of solar and wind power generation with research and innovation activities creates conditions for bringing energy production, technological development, and industrial applications closer together.

This configuration, however, requires the assessment of technologies to consider the environmental specificities of the territory. The availability of renewable electricity does not eliminate the constraints associated with other inputs required for hydrogen production, particularly water. According to Silva et al. (2025), the analysis of the value chain in Ceará should incorporate the water footprint and virtual water flows, since the sustainability of the production system depends on the integration of energy, water, and territory.

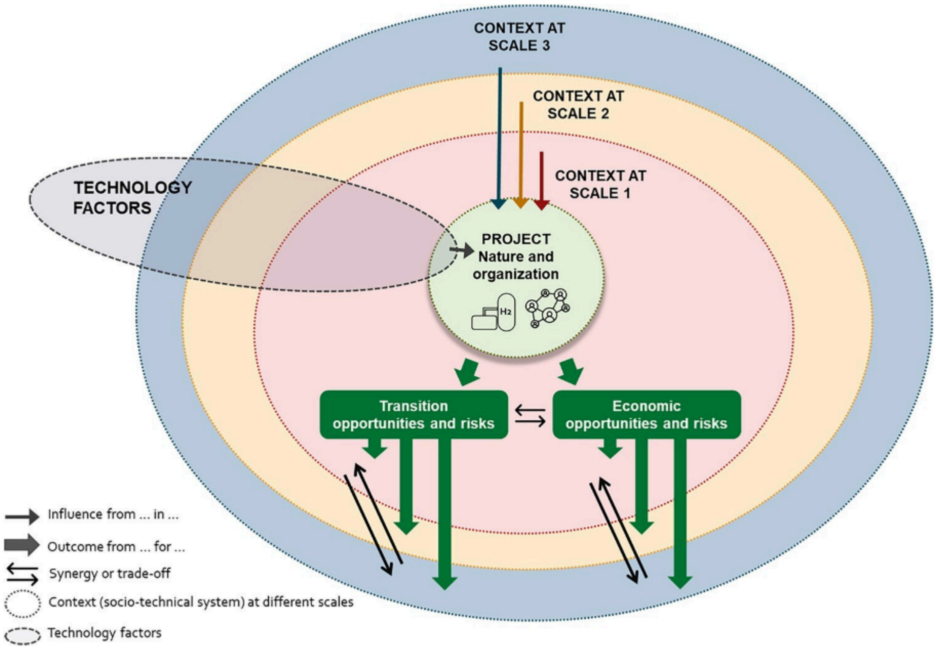
> *It is appropriate to address concerns regarding water supply sources for hydrogen plants, as these may eventually create barriers to sustainable development. This is because arid regions such as the Brazilian Northeast, which are suitable for installing photovoltaic panels or wind turbines, the main sources of electricity for H_2 production, have historically experienced water scarcity (Ceará, 2019; Woods; Bustamante; Aguey-Zinsou, 2022, p. 06).*

The regulatory dimension also forms part of the conditions required for technological innovation to translate into territorial development. In Ceará, the discussion on green hydrogen simultaneously involves incentives for productive activities, environmental protection, water resource management, and consideration of the territories affected by project implementation. According to Queiroz and Monteiro Júnior (2026, p. 12):

> *It is important to emphasize that the regulation of G H_2 production should encompass, beyond market regulation and tax incentives, the guarantee and protection of ways of life, culture, water resources, and situated knowledge in territories that may be affected by its production cycle, as well as mitigation guidelines for such impacts. The absence of specific regulations focused more directly on water resource management is particularly sensitive in the context of the semiarid Northeast, where intermittent droughts and water scarcity already constitute structural factors of vulnerability.*

The study on the Ceará Green Hydrogen Hub proposes a multiscalar analytical framework that more comprehensively integrates technological, environmental, economic, institutional, and territorial factors. Before proceeding, a clarification is warranted: the reference indicated in the original request attributed the study to Lindner et al. (2024), but the publication actually consulted was authored by Clara Caiafa, Henny Romijn, and Heleen de Coninck and published in *Climate Policy* in 2025. The model operates through the interaction among technological characteristics, project configurations, and contextual factors at different scales, linking these dimensions to outcomes, opportunities, risks, and potential conflicts among objectives.

Figure 3. Multiscalar analytical framework for identifying opportunities, risks, synergies, and conflicts in international green hydrogen partnerships



Source: Caiafa, Romijn e Coninck (2025).

The establishment of the Ceará Green Hydrogen Hub represents, in this context, an institutional initiative associated with attracting investments and developing a productive chain linked to renewable energy sources. Bezerra (2021) reports that Ceará created the country's first Green Hydrogen HUB on February 19, 2021, an initiative subsequently followed by other Brazilian states. This movement contributed to increasing the visibility of regional conditions and bringing together economic development policies, energy infrastructure, and technological innovation.

This institutional movement gained concrete expression between 2025 and 2026: the Green Hydrogen Hub at the Pecém Industrial and Port Complex already has seven pre-contracts signed with national and international companies, totaling approximately BRL 60 billion in announced investments and a production target of 1 million tonnes of G H_2 per year by 2032. This volume is projected to meet a significant share of the import demand of the Port of Rotterdam, the hub's strategic partner on the export route between South America and Europe (Complexo do Pecém, 2026a). This progress, however, coexists with structural bottlenecks recognized by the sector itself. The 2026 Strategic Agenda of the Brazilian Green Hydrogen Industry Association, launched with the participation of FIEC, identifies restricted access to the electricity transmission grid, the high concentration of projected demand in the European export market, and the absence of mechanisms to stimulate domestic demand as the main constraints (Sistema FIEC, 2026; Diário do Nordeste, 2026). These bottlenecks reinforce that technological prioritization in Ceará cannot rely solely on the availability of renewable resources and the attraction of investments but must incorporate criteria related to grid infrastructure, market diversification, and local productive linkages.

Among the initiatives aimed at developing the hydrogen productive chain in Brazil, the creation of the country's first Green Hydrogen HUB by the Government of the State of Ceará on February 19, 2021, deserves particular attention. This initiative was followed by the states of Pernambuco, Rio de Janeiro, Bahia, and Minas Gerais, which also announced the creation of green hydrogen HUBs, increasing the visibility of these states' capabilities and facilitating investment attraction (Bezerra, 2021, p. 1).

The economic dimension of the value chain must also be linked to innovation capacity and the development of local skills. Ribeiro and Matos (2025) indicate that the expansion of green hydrogen in Brazil requires investments in technology and transportation and storage infrastructure, while Barbosa et al. (2025) emphasize the need for professional training and public policies capable of supporting the structuring of the sector. In Ceará, this integration is particularly relevant to scientific research, human resource development, and the capacity to develop solutions adapted to the territory's energy, industrial, and environmental conditions.

Ceará's prospective integration into national and international value chains also requires a careful assessment of the technological and economic effects associated with the sector's expansion. Studies on Brazilian green hydrogen indicate opportunities related to exports, sustainability, and the formation of new productive chains, while also pointing to infrastructure, cost, and regulatory barriers (Ribeiro; Matos, 2025). The assessment of technologies should therefore consider their capacity to contribute to innovation and industrial structuring without dissociating these dimensions from the environmental, institutional, and territorial conditions that shape their implementation.

Considering these dimensions, the assessment by specialists should encompass criteria capable of relating innovation, infrastructure, natural resources, scientific development, industrial capacity, skills development, productive integration, and energy transition. The literature reviewed supports the need for an approach that does not reduce technological assessment to the technical performance of each solution in isolation but considers its interaction with the Ceará context. For this purpose, Table 2 systematizes the categories and criteria that may comprise the prioritization instrument to be applied to specialists.

Table 2. Categories and criteria for assessing the relevance and scientific and technological development of green hydrogen technologies in Ceará

Category	Evaluation criterion	Guiding question for specialists
Technological innovation	Capacity to generate or incorporate new	To what extent does the technology foster innovation

	products, processes, and solutions	within Ceará's green hydrogen ecosystem?
Scientific development	Contribution to research, knowledge production, and skills development	To what extent can the technology stimulate scientific research and skills development in Ceará?
Technological maturity	Degree of development and readiness for applications	At what stage of development is the technology for application in the context under consideration?
Industrial applicability	Suitability for existing or planned industrial activities	To what extent can the technology be incorporated into industrial activities in Ceará?
Technological and logistics infrastructure	Compatibility with energy, industrial, port, and logistics infrastructure	To what extent does existing or planned infrastructure facilitate its implementation?
Availability of renewable resources	Compatibility with Ceará's solar and wind conditions	To what extent can the technology be integrated with the availability of renewable energy sources in the state?
Water sustainability	Compatibility with the conditions of water resource availability and management	To what extent does the technology reduce or adequately manage water demands and constraints?
Industrial capacity and value generation	Contribution to value addition, production, and industrial diversification	To what extent can the technology contribute to the development of local productive capacities?
Skills development	Demand for and stimulation of technical and scientific qualification	To what extent does the technology foster the development of specialized professionals in Ceará?

Energy transition	Contribution to replacing higher-emission processes and energy sources	To what extent does the technology contribute to the energy transition and decarbonization?
Integration into productive chains	Capacity to articulate with the other links in the hydrogen system	To what extent does the technology foster integration among production, storage, transportation, and utilization?
Institutional and regulatory suitability	Compatibility with the regulatory and institutional environment	To what extent do institutional and regulatory conditions favor the adoption of the technology?

Source: Prepared by the authors based on Ceará (2019), Woods, Bustamante and Aguey-Zinsou (2022), Bezerra (2021), Queiroz and Monteiro Júnior (2026), Silva et al. (2025), Ribeiro and Matos (2025), Barbosa et al. (2025), Almeida et al. (2025), and Caiafa, Romijn and de Coninck (2025).

The structure presented in Table 2 was developed to enable a multidimensional analysis of specialists' perceptions. The categories interconnect the technological, scientific, industrial, environmental, and institutional domains, thereby enabling the technologies to be compared based on their suitability to the specific conditions of Ceará.

Thus, the instrument supports the achievement of the specific objective of assessing the relevance and potential for scientific and technological development of emerging technologies associated with green hydrogen, establishing a consistent basis for the subsequent prioritization phase.

2.4. Technological Prioritization And Assessment Of Emerging Trends In The Green Hydrogen Value Chain

Prioritizing technologies within the green hydrogen value chain is not a task that can be resolved by considering only the technical maturity of each pathway. The production, storage, transportation, and end uses of green hydrogen involve numerous possible combinations, such that each choice reshapes what constitutes a priority. Ceará has distinct production pathways and end uses that are still being defined.

The aim here is to develop an analysis that articulates technical, economic, institutional, and territorial dimensions and accounts for this interdependence, considering how infrastructure, industry, innovation, regulation, and professional qualification are articulated, or fail to be articulated, within the territory, beyond the development stage of each technology (Silva et al., 2025; Rocha; Pompeu, 2024).

The complexity of this value chain also arises from the need for infrastructure compatible with different technological stages. Ramos et al. (2024, p. 03) explain that:

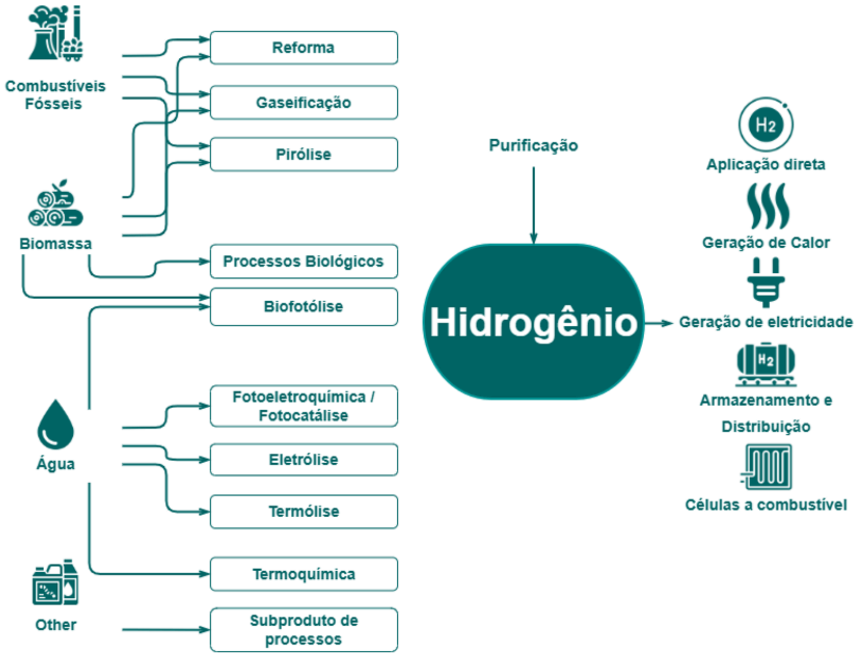
> *The need to develop and expand infrastructure for the production, storage, transportation, and distribution of hydrogen is crucial to driving the transition toward a more sustainable energy matrix. This encompasses the construction of electrolyzers, advanced storage facilities, and the establishment of an efficient distribution network to deliver hydrogen to points of consumption.*

This condition makes infrastructure a criterion directly related to technological prioritization. Griffiths et al. (2021, p. 7) emphasize the sociotechnical and multiscalar nature of the value chain by stating that:

> *[...] due to the high complexity of the green hydrogen value chain and its networks of systems and multiscalar interactions, the legitimization of green H_2 requires stronger government action to promote and develop the workforce, build partnerships, provide investment incentives, and develop a legally secure and regulated business environment. Prioritization must therefore also consider the institutional conditions that support each technological pathway.*

Thus, Figure 4 below helps illustrate the various technological pathways that may be associated with hydrogen production and utilization. The representation encompasses different feedstocks and production methods, as well as the stages of purification, storage, distribution, and end use, thereby enabling the value chain to be understood as a cohesive technological system.

Figure 4. Hydrogen value chain: feedstocks, main production pathways, and general applications



Source: Silva et al. (2025)

The definition of prioritization criteria must also incorporate normative and regulatory dimensions. Therefore, Evangelista, Magalhães, and Mariani (2023, p. 333) explain the extent to which:

> *[...] it is relevant to analyze and understand the main challenges involved in implementing public policies, regulations, and legislation on hydrogen, particularly their interconnection with the already established Brazilian electricity sector, in order to improve the debate, with the expectation that, in the future, regulations on the subject will be capable of promoting the main objectives established and expected for such a promising market.*

Certification constitutes another dimension related to technological differentiation and the reliability of production chains. In this regard, Evangelista, Magalhães, and Marini (2023, p. 462) exemplify that:

> *According to the National Renewable Energy Agency [...], certification is an essential element of every market, especially when establishing a new one. The certification of green hydrogen should, in turn, demonstrate compliance with regulatory standards and requirements, enabling verification based on data and criteria related to sustainability, carbon footprint, and renewable energy content, thereby distinguishing "green" hydrogen from its less or non-"green" variants.*

This aspect can guide the assessment of each technology's capacity to meet verifiable sustainability requirements. With regard to Ceará, technological prioritization should incorporate the interconnection among innovation, industrialization, and the creation of new productive chains. The expansion of the low-carbon hydrogen value chain is linked to the state's green neoindustrialization, according to Rocha and Pompeu (2024), while Gomes et al. (2025) emphasize the importance of considering the various technological pathways for production, storage, and distribution. This makes it possible to assess not only the presence of a technology but also how it integrates into the state's productive system.

Economic analysis, particularly regarding investments, infrastructure, and market presence, complements this perspective. Cardoso Júnior and Silva (2026) examine the market and investment opportunities that green hydrogen may bring to Brazil, while Freitas (2024) focuses on establishing a basis of legitimacy for this agenda in Ceará. From a prioritization perspective, these aspects justify the need to incorporate criteria related to application feasibility, market integration, the institutional environment, and the capacity to coordinate public and private stakeholders.

The relationship among hydrogen, decarbonization, and territorial reorganization must also be incorporated into the assessment instrument. While Feitosa Neto et al. (2026) link *powershoring*, innovation, and decarbonization to the formation of green industrial value chains in Brazil, Schneider, Santos, and Arbache (2026) discuss *powershoring* as a development strategy for the Northeast. In Ceará, this perspective makes it possible to assess how technologies can contribute to the creation of industrial value chains connected to the availability of renewable energy sources and regional development strategies.

Based on these dimensions, the prioritization proposed in this study will be conducted through categories and criteria that enable specialists' opinions to be converted into comparable data. The instrument considers technological maturity, innovation, industrial application feasibility, infrastructure, economic feasibility, market integration, professional training, regulation, certification, and contribution to the energy transition.

Table 3. Categories and criteria for prioritizing emerging technologies in the green hydrogen value chain in Ceará

Prioritization Category	Assessment Criterion	Guiding Question for Specialists
1. Strategic Relevance	Importance of the technology for the development of the green hydrogen value chain in Ceará	What is the strategic relevance of this technology to the consolidation of the green hydrogen value chain in Ceará?

2. Technological Maturity	Degree of development and availability of the technological solution	To what extent does the technology exhibit sufficient maturity to advance toward applications in the Ceará context?
3. Innovation Capacity	Ability to generate technological solutions, processes, products, or knowledge	To what extent does the technology foster scientific and technological innovation in Ceará?
4. Industrial Applicability	Suitability of the technology for industrial activities related to green hydrogen	What is the capacity of the technology to be applied to existing or expanding industrial processes in Ceará?
5. Technological Infrastructure	Compatibility with production, storage, transportation, and distribution infrastructure	To what extent is the infrastructure required for the adoption of the technology compatible with the conditions of Ceará?
6. Economic Feasibility	Conditions for implementation, operation, and integration into economic activities	What is the economic feasibility of adopting this technology in the state context?
7. Integration into Productive Chains	Capacity to integrate with existing or emerging industrial and energy value chains	To what extent can the technology strengthen productive chains related to green hydrogen?
8. Skills Development	Demand for and contribution to professional training and scientific development	To what extent does the technology foster the development of a qualified workforce and knowledge production?

9. Regulatory Compliance and Certification	Compatibility with regulatory, environmental, and certification requirements	To what extent does the technology meet the conditions for regulatory compliance and certification?
10. Contribution to the Energy Transition	Capacity to contribute to decarbonization and the integration of renewable energy sources	To what extent does the technology contribute to the energy transition in Ceará?

Source: Prepared by the authors based on Evangelista, Magalhães, and Mariani (2023); Silva et al. (2025); Rocha and Pompeu (2024); Gomes et al. (2025); Ramos (2024); Freitas (2024); Cardoso Júnior and Silva (2026); Griffiths et al. (2021); Queiroz and Monteiro Júnior (2026); Feitosa Neto et al. (2026); Schneider, Santos, and Arbache (2026).

The combination of the criteria makes it possible to determine which alternatives exhibit greater convergence among technological development, productive applicability, infrastructure, regulation, skills development, and the energy transition. Thus, the prioritization process moves beyond considering exclusively technical attributes and incorporates the specific conditions of Ceará, providing a methodological basis for identifying the technologies that should receive greater attention in scientific and technological analysis.

3. METHODOLOGY

The green hydrogen value chain in Ceará is still taking shape, and this research did not directly engage with any of the actors currently driving its development: no interviews or fieldwork were conducted. The material is entirely secondary, consisting of literature and institutional documents. This choice is related to the nature of the object of study, which articulates technological, scientific, industrial, and territorial dimensions and encompasses different technological pathways within an energy and industrial context characterized by specific conditions. Given this diversity, a qualitative, exploratory approach was considered more appropriate, as it is less concerned with measurement than with understanding relationships, meanings, and trends that quantitative measurement alone would not fully capture. Lösch, Rambo, and Ferreira (2023) and Alexandre (2021) discuss this type of approach for research objects that are still undergoing consolidation, which precisely describes the productive chain investigated here.

The study employed two procedures in an articulated manner: a bibliographic review and documentary research. The bibliographic review surveyed theses, dissertations, monographs, articles published in conference proceedings and scientific journals in Brazil and abroad, book chapters, and books addressing green hydrogen, energy technologies, innovation, and scientific and technological development. This type of survey makes it possible to critically organize the knowledge already produced on a given topic and to recognize where theoretical perspectives converge and where they diverge, an important stage in the systematization of knowledge in research across different fields (Sousa; Oliveira; Alves, 2021).

The documentary research was structured around four institutional and technical documents, all directly related to hydrogen or to the energy conditions of Brazil and Ceará: *Hydrogen in Latin America: From Short-Term Opportunities to Large-Scale Deployment*, by the International Energy Agency (2021); *MasterPlan Hidrogênio Verde Ceará*, by FIEC (2024); *Hidrogênio verde: oportunidades e desafios* *para o Brasil*, by IPEA (2022); and *Ceará: atlas eólico e solar*, by the Government of the State of Ceará (2019). These are records produced in highly specific contexts, including an international report, a state-level plan, a public policy assessment, and an energy potential survey, each incorporating its own guidelines, diagnoses, and technical information. Working with this material adds empirical density to the interpretation that academic literature alone would not provide, particularly in matters of policy, energy planning, and technological transformations (Alves et al., 2021).

The two procedures are closely complementary. The bibliographic review provided the conceptual foundations, including technology, innovation, value chain, and scientific and technological development, while the documentary research connected these dimensions to the energy characteristics and planning strategies identified in the Brazilian and Ceará contexts. This complementarity reduced reliance on a single source of evidence and supported an integrated interpretation of the object of study, in accordance with principles of organization and methodological grounding in scientific research (Alexandre, 2021; Sousa; Oliveira; Alves, 2021; Alves et al., 2021). Accordingly, the methodological strategy adopted proved appropriate by combining procedures with distinct yet complementary functions in the investigation. The qualitative exploratory approach made it possible to interpret the complexity of the object, while the two procedures provided a basis for contrasting scientific perspectives, technical information, and contextual elements related to the green hydrogen value chain. It was the combination of these procedures that supported the construction of the criteria used to examine and prioritize emerging technologies, while maintaining consistency among the research problem, the established objectives, and the research pathway actually followed.

4. FINAL CONSIDERATIONS

Technological prioritization within the green hydrogen value chain in Ceará is situated within a context of transformation in energy, industrial, and innovation systems, in which the articulation among production, storage, transportation, distribution, and utilization technologies is relevant to the structuring of new productive chains. In this scenario, examining emerging trends from a scientific and technological perspective makes it possible to understand different possibilities for organizing the value chain within the Ceará territory, considering its energy, industrial, institutional, and innovation conditions. The research therefore contributes to strengthening the debate on criteria capable of guiding technological decisions related to green hydrogen.

The results achieved indicate that the general objective was met, as were the three specific objectives proposed. Initially, technologies associated with the different stages of the green hydrogen value chain were identified. Subsequently, dimensions related to technological relevance, maturity, innovation, industrial application, markets, infrastructure, knowledge generation, and the energy transition were examined. Finally, the systematization of the criteria and the perceptions of specialists made it possible to establish a prioritization framework consistent with the specific characteristics of Ceará.

In the first topic of the theoretical framework, it was demonstrated that the green hydrogen value chain has a diversified technological configuration, encompassing different production pathways, purification systems, storage alternatives, transportation and distribution structures, and distinct end uses. This diversity demonstrates that technological assessment cannot be restricted to the electrolysis process but must also consider the interdependencies existing throughout the value chain. Silva et al. (2025), Gomes et al. (2025), and Ramos (2024) contribute to this understanding by relating hydrogen production, infrastructure, feasibility, and applications.

In the second topic of the theoretical framework, it was found that the consolidation of green hydrogen in Ceará is associated with the interaction among innovation, infrastructure, regulation, professional training, investments, and the organization of industrial value chains. Rocha and Pompeu (2024) and Freitas (2024) provide insights into aspects related to the structuring of this field in Ceará, while Griffiths et al. (2021) and Queiroz and Monteiro Júnior (2026) demonstrate the need to consider institutional, territorial, and environmental dimensions. In this regard, technological prioritization requires an integrated understanding of the conditions that support its incorporation into the energy and productive system.

In the third topic of the theoretical framework, the research moved from technological characterization toward the construction of assessment and prioritization criteria, articulating technological maturity, innovation, industrial application, market prospects, knowledge generation, infrastructure, sustainability, regulation, and contribution to the energy transition. This approach is consistent with Cardoso Júnior and Silva (2026), Feitosa Neto et al. (2026), and Schneider, Santos, and Arbache (2026), who relate hydrogen, investments, innovation, decarbonization, and new industrial configurations. The proposed framework therefore provides an analytical basis for comparative assessments of different technologies within the value chain.

As a contribution, this article systematizes a technological prioritization approach applied to the Ceará context, articulating technical, economic, industrial, regulatory, environmental, and scientific dimensions within a single analytical matrix. For future research, it is recommended to expand specialist participation, conduct comparative studies among Brazilian states and regions, incorporate multicriteria decision-making methods, and longitudinally monitor the evolution of technological maturity. It is also appropriate to investigate, in specific studies, the infrastructure requirements, water resources, certification, skills development, and industrial integration associated with technologies that receive higher priority in different contexts.

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[1] Undergraduate Student, Electrical and Computer Engineering, São Carlos School of Engineering (EESC/USP).

[2] MBA in Renewable Energy Management. FBUNI/IEL

[3] MBA in Strategic Business Management. USP.

[4] Dr. in Biotechnology - Federal University of Amazonas

[5] Doctoral student in Intellectual Property and Innovation. ACAD INPI.

[6] Dr. in Electrical Engineering - UFC.

[7] Specialization in Environmental Engineering and Basic Sanitation, Centro Universitário Estácio de Sá (SC).

[8] Prof. Dr. In Agricultural Biotechnology (RENORBIO – UFC).

[9] Ph.D. in Genetics, Conservation, and Evolutionary Biology National Institute of Amazonian Research

[10] Postgraduate Degree in Criminal Law from UniAteneu University Center

[11] Master's degree in Physics. UFC.

[12] MBA in Renewable Energy Management. FBUNI/IEL

[13] Ph.D. in Educational Sciences, FCSA (DINTER Program).

[14] Dr. in Biological Sciences (Cultural Title) – FICL; Master's degree in Crop Science – UFC. E-mail: acesse o artigo original para visualizar o e-mail

[15] Doctoral Student at the Academy of the National Institute of Industrial Property

[16] Prof. Dr. In Regional Development from the University of Barcelona

[17] Especialização em Engenharia Ambiental e Saneamento Básico. Universidade Estácio de Sá