

SUSTAINABILITY, TERRITORY, AND CIRCULAR ECONOMY IN THE GREEN HYDROGEN VALUE CHAIN: CHALLENGES AND PROSPECTS FOR THE ENERGY TRANSITION IN BRAZIL

**SUSTENTABILIDADE, TERRITÓRIO E ECONOMIA CIRCULAR NA CADEIA DO
HIDROGÊNIO VERDE: DESAFIOS E PERSPECTIVAS PARA A TRANSIÇÃO
ENERGÉTICA NO BRASIL**

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ABSTRACT

The contemporary energy transition has driven the search for alternatives capable of reducing dependence on fossil fuels and increasing the share of renewable resources in energy systems. In this context, green hydrogen stands out as an alternative associated with decarbonization, energy diversification, and the integration of different productive activities, although its consolidation in Brazil is linked to aspects of sustainability, territorial organization, infrastructure, and the circular economy. This study aimed to analyze the challenges and prospects of the green hydrogen value chain and its contributions to the energy transition in Brazil. The research adopted a qualitative approach and was conducted through a literature review based on dissertations, scientific articles published in journals, and books obtained from academic and institutional repositories, scientific journals, and publishing platforms. The approach made it possible to integrate and interpret the dimensions of sustainability, territory, and the circular economy within the context of the green hydrogen value chain. The results revealed that Brazil's green hydrogen value chain faces challenges related to sustainability, infrastructure, territorial organization, and the circular integration of resources. The findings indicated that its expansion depends on coordination among renewable energy sources, energy and logistics infrastructure, territorial planning, and resource reuse strategies. It is concluded that integrating these dimensions may contribute to the diversification of energy systems and the advancement of Brazil's energy transition.

Keywords: Green hydrogen; Sustainability; Circular economy; Energy transition.

RESUMO

A transição energética contemporânea tem impulsionado a busca

por alternativas capazes de reduzir a dependência de fontes fósseis e ampliar a participação de recursos renováveis nos sistemas energéticos. Nesse contexto, o hidrogênio verde destaca-se como uma alternativa associada à descarbonização, à diversificação energética e à integração de diferentes atividades produtivas, embora sua consolidação no Brasil esteja relacionada a aspectos de sustentabilidade, organização territorial, infraestrutura e economia circular. Este estudo teve como objetivo analisar os desafios e as perspectivas da cadeia do hidrogênio verde e suas contribuições para a transição energética no Brasil. A pesquisa caracteriza-se como qualitativa, desenvolvida por meio de revisão bibliográfica, com base em dissertações, artigos científicos publicados em periódicos e livros, obtidos em repositórios acadêmicos e institucionais, periódicos científicos e plataformas editoriais. A abordagem adotada permitiu articular e interpretar as dimensões da sustentabilidade, do território e da economia circular no contexto da cadeia do hidrogênio verde. Os resultados evidenciaram que a cadeia do hidrogênio verde no Brasil apresenta desafios relacionados à sustentabilidade, à infraestrutura, à organização territorial e à integração circular dos recursos. Constatou-se que sua expansão depende da articulação entre fontes renováveis, infraestrutura energética e logística, planejamento territorial e estratégias de reaproveitamento de recursos. Conclui-se que a integração dessas dimensões pode contribuir para a diversificação dos sistemas energéticos e para o avanço da transição energética brasileira.

Palavras-chave: Hidrogênio verde; Sustentabilidade; Economia circular; Transição energética.

1. INTRODUCTION

Green hydrogen has entered the energy transition debate as one of the possible responses to the dual challenge of reducing dependence on fossil fuels while meeting continuously growing demand for both energy and industrial feedstocks. The interest it generates stems from two main factors: its production is linked to renewable electricity sources, and its applications extend across several productive sectors. However, expanding this value chain cannot be achieved through technological availability alone. It depends on the environmental, territorial, infrastructural, and economic conditions that shape hydrogen production and use, which give the discussion specific characteristics in the Brazilian context.

In Brazil, these conditions have distinctive characteristics. The country has abundant renewable resources, encompasses a highly diverse territory, and has industrial, port, and logistics infrastructure whose degree of integration varies considerably across regions. Consolidating this value chain requires a comprehensive understanding of sustainability, territorial conditions, and infrastructure, as well as an assessment of the extent to which circular economy principles can be incorporated into production processes. By examining these dimensions together, it becomes possible to discuss not only the extent to which production can effectively expand but also the challenges of using resources efficiently and integrating green hydrogen into the country's energy and production systems.

The specific contribution of this study lies in integrating the territorial dimension and circular economy principles into the analysis of Brazil's green hydrogen value chain. This perspective makes it possible to examine jointly how project location, natural

resource availability, energy and logistics infrastructure, and relationships among productive activities shape opportunities for material recovery, resource reuse, and by-product valorization. Accordingly, the sustainability of the value chain is discussed beyond the renewable origin of electricity, also considering the territorial conditions for project implementation and opportunities for circular integration among the different stages of production. The analytical contribution therefore lies in an integrated examination of these dimensions, without assuming that their coordination alone guarantees environmentally or socially sustainable outcomes.

This discussion can be contextualized through initiatives and prospects for the development of production hubs in different Brazilian regions. In Ceará, the Pecém Industrial and Port Complex brings together initiatives aimed at establishing a green hydrogen hub, including arrangements for production projects and the supply of reclaimed water, which is particularly relevant given the water requirements of electrolysis. In Pernambuco, the Suape Industrial Port Complex is developing initiatives associated with the energy transition, low-emission hydrogen production, and derivatives such as e-methanol. In Rio de Janeiro, the Port of Açu has adopted a low-carbon industrialization strategy that encompasses the integration of renewable energy, hydrogen, and industrial demand. These cases provide an opportunity to discuss different territorial and infrastructural configurations, although the initiatives differ in scope and stage of development. Their analysis also highlights the need to assess water availability, electricity grid connections, logistics, industrial integration, and the potential socio-environmental effects of each project.

In this context, the study addresses the following research question: What are the main challenges and prospects associated with Brazil's green hydrogen value chain, considering the dimensions of sustainability, territory, and the circular economy, and how might these factors contribute to the country's energy transition?

The general objective is to analyze the challenges and prospects of the green hydrogen value chain and its contributions to the energy transition in Brazil. To achieve this purpose, three specific objectives were established: (1) to assess the contributions of green hydrogen to sustainability and the energy transition in Brazil, considering greenhouse gas emission reductions, the integration of renewable energy sources, and the diversification of the energy mix; (2) to analyze the influence of territorial characteristics and energy and logistics infrastructure on the development of Brazil's green hydrogen value chain, considering the availability of renewable resources, project locations, transportation, storage, and distribution systems, and integration with industrial hubs; and (3) to investigate opportunities to apply circular economy principles to the green hydrogen value chain, considering resource recovery, by-product valorization, water and energy use efficiency, and integration among different productive activities.

Regarding the methodology, this study adopts a qualitative approach and uses a literature review as its research procedure. Dissertations, scientific articles published in journals, and books obtained from academic and institutional repositories, scientific journals, and publishing platforms were examined to compile knowledge related to sustainability, territory, and the circular economy within the green hydrogen value chain.

The article is organized into four sections. The first is the Introduction, which presents the topic's context, the research question, and the objectives. The second comprises the Theoretical Framework, which brings together the scientific discussion of the dimensions underlying the study. The third presents the Methodology, describing the approach and procedure employed in the investigation. Finally, the fourth section contains the Final Considerations, which summarize the main findings and present the study's contributions to the topic under investigation.

2. THEORETICAL FRAMEWORK

2.1. Sustainability And Energy Transition

The contemporary energy transition is associated with the need to reduce dependence on fossil fuels and increase the share of renewable sources in energy production and consumption systems. This process encompasses environmental, economic, technological, and social dimensions, as transforming energy systems requires changes in generation, infrastructure, industry, and transportation. According to Gorayeb, Brannstrom, and Meireles (2019, p. 67), “[...] the development model based on the intensive use of fossil fuels has resulted in the degradation of natural ecosystems, compromising biodiversity and intensifying global warming.”

The magnitude of this transformation also stems from the continued reliance on fossil fuels across different segments of the global economy. According to Smil (2024, p. 78),

[...] the historical transition from a global energy system dominated by fossil fuels to a new arrangement based exclusively on renewable energy flows poses an enormous challenge (one that is not usually sufficiently appreciated): the ubiquity and magnitude of our dependence on fossil fuels, together with the need for further increases in global energy use, mean that even the most vigorously pursued transition could only be completed over several generations. A complete transition would require replacing fossil fuels not only as the dominant suppliers of different forms of energy but also as crucial sources of raw materials: inputs for ammonia synthesis (approximately 175 Mt/year in 2015, primarily to supply nitrogen for crops) and other fertilizers and agrochemicals (herbicides and pesticides); inputs for the ubiquitous plastics used today, whose total production is approximately 300 Mt/year; and metallurgical coke, which currently requires around 1 Gt of coking coal annually and is used not only as an energy source for reducing iron oxides but also for its structural role in supporting and facilitating the flow of iron ore charged into blast furnaces, which produce more than 1 Gt of iron annually.

In this context, green hydrogen emerges as a technological alternative associated with the production of low-emission energy carriers, particularly when linked to renewable electricity generation. Its role in the energy transition must be understood systemically, considering not only the production stage but also the conditions governing storage, transportation, use, and integration with industrial activities. Gutierrez (2025) emphasizes that Brazil's energy transition involves challenges related to the expansion of low-carbon technologies, energy security, and the need for coordination among different energy sources and sectors.

Hydrogen is an energy carrier rather than a primary energy source. In electrolysis, electrical energy is converted into chemical energy through the overall reaction $2 \text{H}_2\text{O}(\text{l}) \rightarrow 2 \text{H}_2(\text{g}) + \text{O}_2(\text{g})$. Alkaline, proton exchange membrane (PEM), and solid oxide electrolysis technologies differ in terms of operating temperature, flexibility, efficiency, and materials. The value chain also includes water treatment, gas conditioning, compression or conversion into derivatives, transportation, and end use. Therefore, system assessments must explicitly define their analytical boundaries and identify the origin of the electricity used (Irena, 2020; IEA, 2024).

In Brazil, the availability of renewable resources provides favorable conditions for expanding energy systems based on lower-carbon sources. However, diversifying the energy matrix depends on investment, technological innovation, and the capacity to integrate generation, transmission, storage, and consumption. Paixão and Abaide (2026) associate the energy transition with economic development and technological innovation, indicating that transforming energy systems is linked to the incorporation of new solutions and the reorganization of productive structures.

The concept of sustainability adopted in this study is grounded in the Triple Bottom Line (TBL), proposed by Elkington (1997), according to which organizational performance should be assessed through the integrated consideration of economic, social, and environmental dimensions. When applied to the green hydrogen value chain, this perspective indicates that the renewable origin of electricity alone is insufficient to characterize the chain as sustainable. It is also necessary to consider its effects on territories and communities, as well as the economic viability of the projects. Hart (1995), through the Natural Resource-Based View (NRBV),

proposes that the relationship between organizations and the natural environment can be understood through three interrelated strategies: pollution prevention, product stewardship, and sustainable development. The second strategy brings this discussion closer to the life cycle perspective by extending environmental responsibility to all stages of a product's life cycle.

From a sustainability perspective, the analysis of the green hydrogen value chain is not limited to the production stage. Rather, it encompasses the entire process, from the origin of inputs, such as the renewable electricity and water used in electrolysis, to the impacts generated throughout the transformation cycle, including resource consumption, emissions associated with infrastructure, and resulting waste and by-products. From this life cycle perspective, the sustainability of the value chain also depends on how projects are integrated into their territories and interconnected with other energy generation systems.

The carbon intensity of hydrogen can be expressed as the ratio of total greenhouse gas emissions, measured in carbon dioxide equivalent, to the mass of hydrogen produced, in kg CO₂eq/kg H₂. The calculation must account for the stages included within the analytical boundary, such as equipment manufacturing, electricity generation and transmission, water supply, operation, component replacement, logistics, and end of life. Even projects using renewable electricity may produce different results depending on the technology, utilization factor, logistics, and inventory assumptions. Comparing production pathways therefore requires methodological transparency and, where applicable, certification procedures (ISO 14040:2006; ISO 14044:2006; IEA, 2024).

The sustainability of the green hydrogen value chain also depends on how projects are integrated into their territories and broader energy generation systems. Implementing large-scale projects requires alignment among renewable resource availability, electrical infrastructure, water use, logistics, and industrial demand. Barbosa and Gomes (2026) highlight the strategic dimension of the energy transition and Ceará's role in green hydrogen production and exports, illustrating the relationship between territorial resources, technological development, and integration into international markets.

In Brazil, Law No. 14,948/2024 established the legal framework for low-carbon hydrogen, while Law No. 14,990/2024 instituted the Low-Carbon Hydrogen Development Program (PHBC). Consolidating the sector depends on implementing these laws, developing detailed regulations, ensuring emissions traceability, and coordinating industrial, energy, environmental, and territorial policies. The existence of a legal framework does not, by itself, eliminate implementation challenges. Policy assessment must therefore consider the regulatory instruments effectively adopted and their outcomes (Brasil, 2024a, 2024b).

Expanding renewable energy sources also requires systems capable of managing fluctuations in electricity generation and matching supply to consumer needs. In this context, energy storage technologies can support the integration of different sources and contribute to greater operational flexibility in energy systems. Ramos et al. (2026) associate energy storage systems with support for the energy transition and sustainability, highlighting their relationship with the management of generation and consumption in systems based on renewable sources.

The energy transition also has an environmental dimension that extends beyond simply replacing one energy source with another. The expansion of renewable energy must account for its effects on ecosystems, biodiversity, and territories, particularly in regions concentrating new energy projects. Santos et al. (2025) emphasize the need to integrate renewable energy sources, biodiversity conservation, and the green economy in response to the worsening climate crisis, reinforcing the importance of an approach that combines energy performance with environmental protection.

This perspective is particularly relevant given existing inequalities in the distribution of climate impacts. According to Veiga (2019, p. 145), “[...] highly industrialized countries are primarily responsible for CO₂ emissions, but developing nations are the most vulnerable to the impacts of climate change, suffering from extreme weather events, population displacement, and shortages of natural resources.” The energy transition therefore also involves issues of environmental justice, the territorial distribution of benefits and impacts, and institutional capacity for planning.

The relationship between decarbonization and economic development requires consideration of the structural characteristics of energy systems. According to Moreira (2019, p. 78),

[...] the global energy matrix remains predominantly based on fossil fuels, with projections indicating that, despite decarbonization efforts, these sources will continue to account for a significant share of energy production in the coming decades. Transitioning to renewable sources requires not only substantial investment in infrastructure but also structural changes in economic and regulatory models. Dependence on oil, coal, and natural gas is not merely an energy issue but also a geopolitical one, since these resources are concentrated in a limited number of countries, leaving markets vulnerable to crises and price fluctuations.

In this context, the sustainability of the green hydrogen value chain depends on coordinating renewable energy expansion, innovation, infrastructure, and energy planning. Caracas, Gomes et al. (2026) relate the energy transition and technological development to the interfaces among renewable energy, innovation, and intellectual property, while the Brazilian experience highlights the need to structure value chains capable of integrating knowledge, infrastructure, and energy resources. Understanding these relationships makes it possible to view green hydrogen not only as an energy carrier but also as a component of broader technological and economic transformation processes.

To systematize the main elements associated with sustainability and the energy transition in the context of green hydrogen, Table 1 summarizes the environmental, energy-related, technological, territorial, and economic dimensions involved in developing this value chain.

Table 1. Dimensions of sustainability and the energy transition associated with the green hydrogen value chain

Dimension	Aspects Related to Green Hydrogen	Contributions to the Energy Transition
Decarbonization	Reduced dependence on fossil fuels and replacement of energy-intensive, carbon-intensive inputs	Reduction of emissions associated with industrial and energy sectors
Renewable Energy Sources	Integration with solar, wind, and other renewable energy sources	Diversification of the energy mix and increased participation of renewable energy sources
Efficiency and Storage	Integration of energy generation, storage, and consumption	Greater flexibility and improved utilization of renewable electricity
Energy Infrastructure	Need for production, storage, transportation, and distribution systems	Development of new energy and industrial value chains
Territorial Dimension	Relationship between resource availability, project location, and existing infrastructure	Spatial organization of production and integration with industrial hubs
Environmental Sustainability	Consideration of impacts on natural resources, ecosystems, and biodiversity	Compatibility between energy expansion and environmental conservation
Technological Innovation	Development and adoption of technologies for hydrogen production, storage, and utilization	Expansion of technological and productive capacity

Economic Development	Formation of new production value chains and integration with industrial activities	Generation of economic opportunities associated with the energy transition
Energy Security	Diversification of energy sources and reduced dependence on fossil inputs	Greater diversification and resilience of energy systems
Governance and Regulation	Public policies, planning, and regulatory mechanisms for expanding the value chain	Establishment of institutional conditions for investment and technological development

Source: Prepared based on Gorayeb, Brannstrom, and Meireles (2019), Moreira (2019), Veiga (2019), Smil (2024), Gutierrez (2025), Santos et al. (2025), Caracas and Gomes et al. (2026), Barbosa and Gomes (2026), Paixão and Abaide (2026), and Ramos et al. (2026).

The synthesis presented in Table 1 demonstrates that the sustainability of the green hydrogen value chain results from the interaction of multiple dimensions and is not limited to the renewable origin of the electricity used in production. Factors such as infrastructure, territorial characteristics, innovation, energy security, environmental conservation, and economic organization shape how this value chain can be integrated into productive systems. Accordingly, its contribution to Brazil's energy transition depends on an integrated approach to technological development, energy planning, and territorial sustainability.

2.2. Territorial And Infrastructure Dimension

Territorial characteristics play a decisive role in shaping the green hydrogen value chain, as no project is developed in isolation from its

geographical context. Its implementation depends on the location of renewable energy resources, the availability of existing energy infrastructure, and the logistical conditions of the area. These factors are particularly relevant in Brazil, where solar and wind resources, industrial centers, and port facilities are unevenly distributed across the country. This spatial distribution influences where green hydrogen can be produced, how it can be transported, and where it can be used.

However, the availability of abundant solar or wind resources is not sufficient to ensure project feasibility. These resources must be considered alongside electricity grids, water supply systems, industrial facilities, storage infrastructure, and transportation alternatives connecting production units to consumer markets. Without this infrastructure, natural resource availability alone cannot guarantee effective production and distribution. Santos and Oliveira (2024) highlighted this relationship by examining Brazilian energy supply conditions in relation to the technical and structural requirements of actual projects. Existing infrastructure, or its absence, ultimately helps determine which territories are viable for development and which remain only potential locations, regardless of the quality of their natural resources.

The stoichiometry of water electrolysis indicates a minimum water requirement of approximately 9 L per kilogram of H_2 produced. Total operational demand may be higher because it also includes water treatment, cooling, and auxiliary services. Water intensity should therefore be expressed as the total volume of water used per unit of hydrogen produced, in L/kg H_2 , distinguishing water withdrawal, consumption, and reuse. In coastal areas, desalination may represent an alternative, provided that seawater intake, energy

consumption, concentrate disposal, and cumulative environmental impacts are assessed. In semiarid regions, the opportunity cost of water and the water security of local communities should be incorporated into project planning (Irena, 2020; ISO 14040:2006; ISO 14044:2006).

Project location also establishes relationships with industrialization processes and the development of new logistics corridors. Proximity among production facilities, renewable energy generation sites, industrial centers, and port facilities can support value chain integration and reduce intermediate transportation requirements. In this regard, Wang et al. (2023) emphasize that hydrogen supply chains require coordinated logistics infrastructure in which transportation corridors and connection points play an important role in the movement of this energy carrier.

In Brazil, ports occupy a strategic position because of their potential to integrate production, storage, industrial processing, and exports. However, port infrastructure must be supported by land transportation systems and facilities suitable for storing and handling hydrogen and its derivatives. Silva, Leite, and Ferreira (2023) examine the relationship between port infrastructure and green hydrogen logistics in Brazil, indicating that the consolidation of this value chain requires integrated planning involving port facilities, transportation systems, and production and consumption areas.

In Ceará, this integration can be observed at the Pecém Industrial and Port Complex (CIPP), located between Caucaia and São Gonçalo do Amarante, where Brazil's first green hydrogen molecule was produced in 2023 at an EDP facility (Ceará, 2023). In 2024, the state government signed a preliminary agreement worth BRL 9 billion

with the Norwegian company Fuella AS for the installation of a green hydrogen and green ammonia production facility within the complex (Ceará, 2024). The complex encompasses investment projects totaling more than BRL 185 billion for the 2026–2030 period (Complexo do Pecém, [20--]). The concentration of these projects around an existing port structure integrated with industrial areas illustrates the relationship between established infrastructure and the capacity to attract investments across the value chain. This relationship is also highlighted by Barbosa and Gomes (2026) in their discussion of Ceará's integration into green hydrogen production and export markets.

The production, storage, and transportation stages also present technical challenges that influence the spatial configuration of the value chain. Hydrogen's physicochemical properties impose specific requirements for its handling and storage, making it necessary to assess different technological alternatives according to project scale and intended application. Puga and Asencios (2023) discuss advances and limitations in green hydrogen production, storage, and transportation, demonstrating that value chain expansion depends on the coordination of technological solutions with infrastructure compatible with operational requirements.

The territorial dimension also encompasses governance, planning, and coordination among public and private stakeholders. The implementation of large-scale energy projects can transform existing economic and spatial relationships, requiring mechanisms to reconcile investments, land-use planning, infrastructure development, and social interests. Nascimento et al. (2023) associate territorial governance with Brazil's energy transition, reinforcing the

importance of planning processes that coordinate national, regional, and local levels in organizing energy-related transformations.

The location of a green hydrogen hub should account for the availability of renewable energy resources and water, electricity grid capacity, proximity to ports and industrial facilities, consumer markets, ecological sensitivity, and traditional territorial activities. Territory should not be treated as an empty space, since communities, fishing, agriculture, tourism, and environmental heritage coexist within it. Planning must therefore consider cumulative impacts, competing land uses, local employment generation, public participation, and benefit-sharing mechanisms. From an energy justice perspective, it is important to assess who receives the economic benefits and who bears the territorial costs of the energy transition. These considerations should be integrated with territorial governance and evidence concerning the social and environmental impacts of energy projects (Nascimento et al., 2023; Gorayeb, Brannstrom, and Meireles, 2019).

The infrastructure required for the green hydrogen value chain also has a geoeconomic dimension associated with the availability of strategic resources, investment locations, and connections between producing territories and consumer markets. In this context, the capacity of particular territories to combine renewable resources, infrastructure, and industrial activities may influence their integration into emerging energy value chains. Feitosa Neto et al. (2026) relate the geoeconomics of the energy transition to the geopolitics of strategic resources, highlighting the relevance of these relationships to sustainable development in Brazil.

The interaction among territorial characteristics, infrastructure, and markets also affects the value chain's expansion capacity and the formation of specialized hubs. Project implementation can promote integration among renewable energy generation, hydrogen production, industrial activities, and export facilities, provided that adequate infrastructure is available to support these connections. Rocha (2023) examines the prospects and challenges of green hydrogen in Brazil, while Barbosa et al. (2025) provide an overview of the opportunities and challenges associated with the development of this energy value chain in the country.

Brazil has potential advantages associated with the substantial contribution of renewable sources to electricity generation and the complementarity of wind and solar resources. In the Northeast, the combination of these resources with port complexes and industrial facilities may support the development of production and processing hubs. The Pecém Complex in Ceará provides a relevant case for examining the potential integration of renewable energy generation, electricity transmission, industry, electrolysis, and exports. Its territorial feasibility, however, requires specific assessments of water supply, electricity networks, land use, logistics, coastal ecosystems, and community participation. Because this research is based on a literature review, the discussion does not replace fieldwork or an environmental assessment of a specific project (EPE, 2025; IEA, 2024; Barbosa and Gomes, 2026).

To systematize the main relationships among territory, infrastructure, and the development of the green hydrogen value chain, Table 2 presents the factors associated with location, production, storage, transportation, and industrial integration.

Table 2. Territorial and infrastructure dimensions of the green hydrogen value chain: qualitative analysis and quantitative indicators

Dimension	Main Element	Implications for the Green Hydrogen Value Chain	Quantitative Indicators and Comparison Benchmarks
Renewable Natural Resources	Availability of solar and wind energy	Determines the conditions for renewable electricity supply and influences project location.	Generation potential (GW); installed capacity (MW); capacity factor (%); annual generation (MWh/year).
Project Location	Proximity to renewable energy sources, industries, and ports	Influences logistics costs, productive integration, and access to consumer markets.	Distance between production facilities, industrial sites, and ports (km); transportation time (h); logistics cost (R\$/kg H ₂ or US\$/kg H ₂).
Energy Infrastructure	Electricity generation, transmission, and grid connection capacity	Determines electricity supply and the operational continuity of electrolyzers.	Available electrical capacity (MW); electrolysis capacity (MW); utilization factor (%); specific electricity consumption (kWh/kg H ₂).
Water Availability	Water supply and reuse potential	Affects the feasibility of electrolysis and the pressure on local water resources.	Water consumption (L/kg H ₂); available water supply (m ³ /day); percentage of reused water (%).
Storage	Conditioning technology	Determines volumetric	Compressed H ₂ at 350 bar: approximately 23–

	and storage capacity	density, operating conditions, and safety requirements.	24 kg H ₂ /m ³ ; at 700 bar: 39–40 kg H ₂ /m ³ . Liquid H ₂ : approximately 71 kg H ₂ /m ³ . Ammonia: approximately 108–121 kg H ₂ equivalent/m ³ . LOHC: approximately 47–55 kg H ₂ equivalent/m ³ , depending on the compound and reference conditions.
Transportation	Mode, distance, conditioning, and system integration	Influences delivery costs, energy efficiency, and the quantity of hydrogen available to the consumer.	Distance traveled (km); energy consumption (kWh/kg H ₂); transportation cost (R\$/kg H ₂); physical losses (% due to operation or over time). For liquid H ₂ , boil-off losses may be approximately 0.4% per day in 50 m ³ tanks and 0.06% per day in 20,000 m ³ tanks, depending on system conditions.
Port Infrastructure	Terminals, storage, handling, and export operations	Enables connections to international routes and integration with maritime transportation of fuels and derivatives.	Handling capacity (t/year); storage capacity (m ³); number of operational terminals; port operating time (h).

Industrial Hubs	Concentration of producers, suppliers, and consumers	Promotes economies of scale, infrastructure sharing, and integration between production and industrial demand.	Planned and installed capacity (t H ₂ /year); number of projects at each implementation stage; announced investment (R\$); estimated industrial demand (t/year).
Territorial Governance	Planning, regulation, and institutional coordination	Influences licensing, infrastructure deployment, and the territorial distribution of costs and benefits.	Number of licensed projects; licensing time (months); contracted investments (R\$); proportion of projects in operation (%).
Geographical and Productive Integration	Coordination among energy, water, industry, logistics, and markets	Can promote resource utilization, water reuse, and by-product valorization, provided that technical and economic conditions are met.	Volume of reused water (m ³ /year); quantity of valorized by-products (t/year); recovered energy (MWh/year); percentage of reused inputs (%).

Source: Prepared based on Puga and Asencios (2023), Nascimento et al. (2023), Silva, Leite, and Ferreira (2023), Wang et al. (2023), Santos and Oliveira (2024), Rocha (2023), BloombergNEF (2020), Barbosa et al. (2025), and Feitosa Neto et al. (2026).

Notes:

1. Volumetric density values are approximate reference values, not performance measurements from specific facilities. For ammonia and liquid organic hydrogen carriers (LOHCs), they represent the equivalent amount of hydrogen contained in the carrier, rather than free hydrogen. Effective capacity depends on composition, operating conditions, and, where applicable, H₂ recovery efficiency.
2. Water consumption, energy consumption, and logistical losses should be associated with clearly defined production, storage, and transportation conditions. The boil-off rate of liquid hydrogen should not be generalized across all storage tanks or transportation methods.
3. For territorial and port-related indicators, data from official sources concerning the projects under examination should be included. When verifiable information is unavailable, the expression “not reported in the consulted source” should be used instead of estimating values without supporting evidence.
4. Announced investments should not be confused with investments actually executed. Likewise, projected capacity does not correspond to installed or operational capacity.

Table 2 organizes the territorial and infrastructure dimensions of the green hydrogen value chain by presenting qualitative aspects alongside quantitative indicators related to natural resource availability, energy infrastructure, storage, transportation, industrial location, and territorial governance. The table was developed based on the recognition that the expansion of the value chain cannot be

sustained by any single factor. Rather, its feasibility depends on the alignment of territorial resources, technology, logistics, and institutional planning, and the indicators seek to capture these interrelationships. The indicators allow comparisons among technological alternatives, provided that they are interpreted in accordance with their units of measurement, operating conditions, and applicability limitations. This interpretation is not always straightforward when data are obtained from heterogeneous sources. Without such considerations, the comparisons lose analytical validity. In Brazil, the development of logistics corridors and production hubs depends on the compatibility among hydrogen supply, existing infrastructure, and industrial demand, as well as on coordination among the stakeholders involved, which remains one of the most challenging aspects to address.

2.3. Circular Economy Applied To Green Hydrogen

The application of circular economy principles to the green hydrogen value chain extends beyond the production of this energy carrier. It encompasses resource utilization, the identification of losses, the valorization of by-products, and the interconnection of production processes. This approach directly links the energy transition to the principles of resource efficiency and waste reduction, shifting the understanding of the hydrogen value chain from a closed system to a component of interconnected production systems. Yáñez et al. (2018) address this perspective by examining the reuse of surplus hydrogen, which, according to the authors, can contribute to the development of more sustainable supply chains, particularly when strategies are implemented to recover and valorize this resource.

Process integration is one of the foundations connecting hydrogen production with the circular economy. When energy, materials, and by-products circulate in a coordinated manner across different operations, losses tend to decrease and production system efficiency improves. Klemes et al. (2019) examine this relationship by associating process integration with circular principles in the context of renewable and sustainable energy systems. According to the authors, connecting different operations enables more effective use of available resources and improves overall system performance, rather than optimizing each stage independently.

In Brazil, the circular economy can also be linked to energy transition strategies involving hydrogen. Eliziário et al. (2021) discuss the role of hydrogen in the circular economy, relating its use to waste recovery, carbon capture, utilization and storage, and the energy transition. This approach broadens the understanding of the value chain by considering how different material and energy flows can be coordinated within integrated production systems, reducing waste and promoting resource utilization.

Waste valorization represents another opportunity to integrate circular economy principles with hydrogen production. Processes designed to recover materials and convert waste into hydrogen can combine energy generation with the treatment of materials that would otherwise be discarded. Ng and Phan (2021) analyze integrated systems for material recovery and hydrogen production from waste, demonstrating the possibility of combining resource recovery and the generation of an energy carrier within a single production structure.

Circularity seeks to replace the linear flow of extraction, production, and disposal with strategies involving reduction, repair, reuse, remanufacturing, recovery, and recycling. Electrolyzers, wind turbines, and photovoltaic modules contain metals and other materials whose recovery should be considered from the design stage. As a preliminary indicator, the material recovery rate can be calculated as the ratio of the recovered mass to the total mass considered, multiplied by 100. Electrolysis also theoretically produces approximately 8 kg of oxygen per kilogram of hydrogen. Its commercial utilization depends on purity, local demand, and logistics. Residual heat can also be used in compatible industrial processes, supporting the development of industrial symbiosis networks. The assessment of these alternatives should consider life cycle impacts and the technical conditions of each application (ISO 14040:2006; ISO 14044:2006; Irena, 2020).

Applying these principles requires considering the hydrogen value chain across its different stages, from production to storage, distribution, and end uses. The organization of efficient production chains depends on infrastructure, public policies, investments, and regulatory conditions that support integration among the various stakeholders. Siffert and Rocha (2023) highlight opportunities and challenges associated with green hydrogen in Brazil, emphasizing the need to establish a production chain capable of connecting different economic activities and institutional conditions.

The circular economy must also be examined in conjunction with the evolution of the hydrogen economy itself. Expanding production, industrial applications, and transportation and storage infrastructure requires supply systems capable of connecting producers, consumers, and infrastructure. The International Energy

Agency (2024) provides an international overview of hydrogen, covering production, demand, infrastructure, and expansion challenges. These elements help explain the organization of the value chain as an integrated system of energy, material, and economic flows.

To systematize the main relationships between the circular economy and the green hydrogen value chain, Table 3 presents resource recovery strategies, process integration, resource valorization, and systems-level assessment approaches associated with the development of this value chain.

Table 3. Circular economy strategies applied to the green hydrogen value chain

Dimension	Strategies and Applications	Contributions to the Green Hydrogen Value Chain
Hydrogen Reuse	Recovery and utilization of surplus hydrogen	Reduction of losses and improved utilization of production flows
Process Integration	Coordination among industrial, energy, and material operations	Greater resource-use efficiency and integration across processes
Material Recovery	Utilization of materials present in waste	Reduction of waste disposal and valorization of secondary resources
Waste-to-Hydrogen Production	Conversion of waste into hydrogen	Integration of waste treatment and energy carrier generation
Efficient Water Use	Management, recovery, and reuse of water flows	Reduced resource consumption and

		improved operational efficiency
Energy Efficiency	Integration of renewable energy generation, hydrogen production, and utilization	Improved utilization of available energy
By-product Valorization	Utilization of material and energy flows derived from processes	Enhanced economic value generation from resources
Supply Chain Integration	Integration of production, storage, transportation, and consumption	Systematic coordination of value chain flows
Life Cycle Assessment	Consideration of environmental impacts throughout the production stages	Identification of opportunities for environmental improvement
Intersectoral Integration	Connections between hydrogen, industry, waste, and other sectors	Development of more integrated and circular production systems

Source: Prepared based on Yáñez et al. (2018), Klemes et al. (2019), Eliziário et al. (2021), Ng and Phan (2021), Siffert and Rocha (2023), International Energy Agency (2024), Shamoushaki and Koh (2026), and Kundu et al. (2026).

The sustainability of the value chain is also associated with the combination of the energy mix employed, supply chain characteristics, and the resources used throughout the processes. As Shamoushaki and Koh (2026) emphasize, the sustainability of green hydrogen technologies depends on the energy systems in which they are integrated and on supply chain conditions. Therefore, the use of renewable energy sources should be complemented by strategies for organizing and managing resources throughout the

different stages of the value chain. A systems-level assessment of the relationship between the circular economy and green hydrogen is thus necessary, taking into account materials, energy, water, waste, infrastructure, and life cycle impacts.

Kundu et al. (2026) connect green hydrogen pathways with the circular economy, life cycle assessment, and technological and safety dimensions, emphasizing the need to examine the different links in the value chain collectively. From this perspective, circularity broadens the sustainability discussion by linking hydrogen production to resource flow optimization and synergies with other economic sectors.

These principles can be applied to develop a more interconnected green hydrogen value chain in which waste, surplus energy, materials, and by-products are incorporated into resource valorization and reuse strategies. The interconnection of production, consumption, and resource recovery reinforces circular economy principles and expands opportunities for collaboration with other sectors. Circularity therefore represents a relevant perspective for analyzing the challenges and opportunities associated with green hydrogen in Brazil, particularly regarding resource efficiency, process sustainability, and the integrated organization of production chains.

Applying these principles could help establish a more integrated green hydrogen value chain in which waste, surplus energy, materials, and by-products are no longer treated merely as residual outputs but are incorporated into valorization and reuse strategies. When production, consumption, and resource recovery are considered collectively, the value chain becomes more aligned with circular economy principles and better positioned to integrate with

other sectors. Circularity is therefore a relevant dimension for examining the challenges and prospects of green hydrogen in Brazil, particularly when considered alongside resource efficiency, process sustainability, and the interconnections among production chains.

2.3.1. Environmental Impacts And Nature-Based Solutions In The Green Hydrogen Value Chain

Although green hydrogen is closely associated with reducing greenhouse gas emissions, its production and geographical expansion are not free from environmental consequences. These impacts can occur at various stages of the value chain, from the installation of solar and wind farms and the construction of transmission lines to water use in electrolysis, the establishment of industrial facilities, storage, transportation, and port operations. Therefore, for hydrogen to be considered “green,” it is not sufficient for the electricity used in its production to come from renewable sources. The environmental performance of the entire production and logistics system must also be assessed (IEA, 2024).

One of the main environmental challenges concerns water availability. Electrolysis requires water of suitable quality, and in water-stressed areas, the expansion of projects may intensify conflicts among industrial, urban, agricultural, and ecological uses. Where desalination facilities are employed, additional energy consumption, brine disposal methods, and potential impacts on coastal ecosystems must also be considered. Furthermore, the construction of renewable energy projects and their associated infrastructure can result in vegetation clearance, habitat fragmentation, landscape alteration, and increased pressure on areas of high biodiversity. These issues highlight the need for

cumulative environmental impact assessments and integrated territorial planning, particularly in Brazil's coastal and semiarid regions.

In this context, Nature-based Solutions (NbS) can complement conventional strategies for environmental impact prevention, control, and restoration. The International Union for Conservation of Nature defines NbS as approaches aimed at protecting, restoring, and sustainably managing natural or modified ecosystems to address societal challenges while generating benefits for biodiversity and human well-being (IUCN, 2020).

In the green hydrogen value chain, these approaches may include riparian forest restoration, the rehabilitation of water recharge areas and wetlands, the establishment of ecological corridors, sustainable watershed management, and the restoration of degraded areas affected by infrastructure development.

Implementing these practices can help control erosion, improve water infiltration and quality, protect springs, reduce sedimentation risks, and strengthen territorial resilience to severe climatic events. In regions being considered for solar, wind, industrial, and port projects, ecological restoration and the preservation of biodiversity corridors can help mitigate habitat fragmentation and the loss of ecosystem services. However, NbS should not be regarded as substitutes for impact prevention, environmental licensing, or emissions reduction at the source. Their implementation should follow a mitigation hierarchy that prioritizes avoiding and minimizing impacts, restoring affected areas, and adopting duly justified compensatory measures only as a last resort (Seddon et al., 2021).

The effectiveness of NbS also depends on how well they are adapted to the ecological, social, and economic characteristics of each region. When solutions are imposed without local community participation, performance indicators, or long-term monitoring, their results may be limited and may even generate conflicts over access to land, water, and natural resources. Green hydrogen projects should therefore be guided by environmental justice, the inclusion of local communities, the protection of sensitive areas, and the equitable distribution of economic benefits. Current climate assessments emphasize that ecosystem-based actions are more effective when integrated with policies for climate adaptation, biodiversity conservation, and the reduction of social vulnerabilities (IPCC, 2022).

Integrating nature-based solutions, the circular economy, and territorial planning strengthens the sustainability of the green hydrogen value chain. Water recovery and reuse, waste valorization, by-product utilization, and the restoration of degraded areas can be planned jointly within industrial and energy hubs. This integrated approach makes it possible to assess the value chain not only in terms of the amount of hydrogen produced or emissions avoided, but also through water and energy efficiency, biodiversity conservation, environmental quality, and the generation of lasting territorial benefits. NbS therefore represent an additional strategy for balancing the expansion of green hydrogen with ecological integrity and the socioenvironmental resilience of Brazil's diverse territories.

3. METHODOLOGY

The study examines sustainability, territorial development, and the circular economy in the green hydrogen value chain, considering the challenges and prospects of its expansion in Brazil and its

contribution to the energy transition. The complexity of these dimensions requires a methodological approach capable of integrating different scientific perspectives and interpreting the interrelationships among technological, environmental, territorial, and productive aspects.

The study adopts a qualitative approach, as it enables an integrated interpretation of the knowledge developed on the research subject, taking into account the concepts, relationships, arguments, and perspectives presented in the scientific literature. In the current research landscape, this approach is particularly relevant to scientific inquiry at the international level, especially in studies addressing complex phenomena involving multiple dimensions, for which contextual and interpretive understanding is fundamental to the construction of scientific knowledge (Denzin and Lincoln, 2018; Risemberg, Wakin, and Shitsuka, 2026).

Two complementary research procedures were employed: bibliographic research and documentary research. Bibliographic research, already described in the preceding paragraphs, provided the theoretical and conceptual foundation for examining green hydrogen, sustainability, the energy transition, territorial development, infrastructure, and the circular economy. Documentary research complemented this procedure by enabling the examination of institutional publications, technical reports, government communications, and other documents containing information relevant to the research problem. This procedure is particularly important in qualitative research because it allows the contextual interpretation of information produced for different institutional and social purposes, helping to identify historical circumstances, policy orientations, regulatory frameworks,

technological developments, and economic perspectives that may not be fully captured by the scientific literature alone. Documentary analysis also supports the critical examination of the origin, context, content, and relevance of the materials selected, contributing to a more consistent interpretation of the phenomenon under investigation (Cellard, 2019).

The bibliographic review drew on dissertations, scientific articles published in specialized journals, and books addressing green hydrogen, sustainability, the energy transition, territorial development, infrastructure, and the circular economy. Sources were consulted through academic and institutional repositories, scientific journals, publishing houses, and platforms providing access to scientific literature, with particular attention to their relevance to the research subject.

The bibliographic review is an important procedure in scientific research because it enables the identification, organization, and interpretation of existing knowledge on a given topic, thereby supporting the conceptual definition of the research subject and the integration of different theoretical contributions. Furthermore, this procedure facilitates the identification of recurring approaches, the comparison of theoretical and scientific perspectives, and the development of a consistent and coherent theoretical foundation for the investigation (Arantes, 2025).

Accordingly, dissertations, scientific articles, and books were selected based on their direct relevance to the dimensions addressed in the study. The literature was analyzed in an integrated manner to clarify how scientific knowledge addresses the green hydrogen value chain and its interrelationships with sustainability,

territorial organization, infrastructure, and the principles of the circular economy.

The documentary research examined seven institutional and technical publications selected according to their relevance to the research objectives and their contributions to understanding the technological, environmental, territorial, and economic dimensions of the green hydrogen value chain. These documents comprised *Hydrogen Economy Outlook: Key Messages*, published by BloombergNEF (BNEF, 2020); two publications by the Government of the State of Ceará concerning the production of the first molecule of green hydrogen in Brazil, announced in January 2023, and the signing of a pre-contract for the installation of a green hydrogen plant in Pecém in October 2024 (Ceará, 2023, 2024); the institutional presentation of the Pecém Complex (Complexo do Pecém, [20--]); *Climate Change 2022: Impacts, Adaptation and Vulnerability*, published by the Intergovernmental Panel on Climate Change (IPCC, 2022); *Global Hydrogen Review 2024*, published by the International Energy Agency (IEA, 2024); and *Global Standard for Nature-based Solutions: A User-Friendly Framework for the Verification, Design and Scaling Up of NbS*, published by the International Union for Conservation of Nature (IUCN, 2020).

These documents were analyzed to identify information relevant to the development of the green hydrogen value chain in Brazil, with particular attention to the institutional and territorial context of Ceará and the Pecém Complex, the technological and economic prospects of hydrogen production, the infrastructure required for its expansion, and the environmental conditions associated with the energy transition. The international publications provided broader analytical references for examining the hydrogen economy, the

development of hydrogen markets, climate change impacts, and environmental sustainability. The government communications and institutional materials, in turn, contributed contextual information on initiatives, investment announcements, and infrastructure associated with the development of the sector in Ceará. The documents were therefore considered complementary sources of evidence rather than interchangeable materials, given their different institutional purposes, scopes, and types of information.

The documentary analysis involved the examination and interpretation of the selected materials in relation to the research objectives and the conceptual dimensions established through the bibliographic review. This procedure enabled the identification of convergences, complementary perspectives, and relevant differences between theoretical discussions and institutional information. It also supported the contextualization of the opportunities and constraints associated with green hydrogen development, particularly regarding infrastructure, territorial organization, environmental considerations, and the integration of productive activities. The documents were interpreted critically, taking into account their origin, purpose, institutional context, and relevance to the issues investigated, in accordance with the principles of qualitative documentary analysis (Cellard, 2019).

The qualitative methodology was appropriate to the nature of the research because it enabled a contextualized interpretation of information obtained from bibliographic and documentary sources without reducing the analysis to numerical data. Within a qualitative approach, the social, historical, environmental, and institutional conditions surrounding research subjects must be considered to

achieve a more comprehensive understanding of complex phenomena (Denzin and Lincoln, 2018).

The integration of bibliographic and documentary research facilitated connections among fields of knowledge related to the research topic. The scientific literature provided the theoretical foundations for interpreting the relationships among green hydrogen production, sustainability, territorial development, infrastructure, and the circular economy, while the documentary sources contributed institutional, technical, environmental, and contextual information relevant to the Brazilian setting. This combination supported a more comprehensive examination of the research problem and helped relate conceptual discussions to the conditions and initiatives associated with the development of the green hydrogen value chain (Arantes, 2025; Cellard, 2019; Risemberg, Wakin, and Shitsuka, 2026).

The combination of these two research procedures, within a qualitative framework, was therefore appropriate because it enabled a critical interpretation of diverse scientific and documentary contributions and their integration with the dimensions structuring the study. This methodological approach supported a holistic understanding of the phenomenon under investigation while preserving the complexity of the interrelationships among energy, territory, sustainability, infrastructure, and the organization of production processes. The findings were consequently developed through the interpretive synthesis of the selected sources, rather than through fieldwork, interviews, or the collection of primary empirical data.

FINAL CONSIDERATIONS

The green hydrogen value chain is a research topic directly connected to the challenges of the energy transition, particularly regarding sustainability, territorial development, and the circular economy. In this context, the study entitled *Sustainability, Territory, and Circular Economy in the Green Hydrogen Value Chain: Challenges and Prospects for the Energy Transition in Brazil* integrated several dimensions that influence the development of this value chain in Brazil. This integrated approach helped establish that its expansion is not limited to hydrogen production from renewable sources, but also encompasses infrastructure, territorial organization, resource-use efficiency, and connections among different production activities.

Green hydrogen can contribute to decarbonization in Brazil, but its sustainability depends on the entire production chain. The use of renewable electricity does not eliminate the need for life cycle assessment, water management, territorial planning, material recovery, and social participation. The development of circular industrial hubs may increase domestic value added, particularly in regions such as the Northeast.

The research question, “What are the main challenges and prospects associated with the green hydrogen value chain in Brazil, considering the dimensions of sustainability, territory, and the circular economy, and how can these factors contribute to the country's energy transition?”, was addressed throughout the study. The analysis indicated that the main bottlenecks concern the coordination of renewable energy expansion, energy and logistics infrastructure, territorial organization, storage, transportation, resource availability, and production integration. Conversely, development prospects are associated with the formation of

integrated production chains and the adoption of practices capable of improving resource-use efficiency and the sustainability of energy systems.

The general objective, which was to analyze the challenges and prospects of the green hydrogen value chain and its contributions to the energy transition in Brazil, was achieved through the integration of the three dimensions investigated. The specific objectives were also addressed. The first was fulfilled by examining the contributions of green hydrogen to sustainability and the energy transition. The second was addressed through an analysis of the influence of territorial characteristics and energy and logistics infrastructure. The third was fulfilled by investigating the possibilities of applying circular economy principles, particularly regarding resource recovery, by-product valorization, water and energy efficiency, and synergies among production activities. Thus, the achievement of the objectives stems from the integrated analysis conducted rather than merely from their formal restatement in this section.

Regarding the first theoretical dimension, the study established that green hydrogen can contribute to increasing the share of renewable energy sources, reducing dependence on fossil fuels, and diversifying energy mixes. However, the sustainability of this transition requires consideration of environmental impacts, necessary infrastructure, energy efficiency, and the economic and institutional conditions associated with adopting new technologies. Green hydrogen production should therefore be understood as part of a broader transformation of energy systems, whose outcomes depend on the conditions under which technologies are implemented and integrated into economic activities.

The second dimension revealed that territory and infrastructure condition the implementation and expansion of the green hydrogen value chain. Renewable resources must be integrated with electricity infrastructure, water supply, storage and transportation systems, port facilities, and proximity to industrial centers and consumer markets. The spatial distribution of these elements influences the configuration of production chains and requires integrated planning across different territorial scales, supported by coordinated participation among stakeholders. Key strategic bottlenecks include aligning project locations with available infrastructure, ensuring water supply, developing appropriate storage and transportation solutions, and bringing hydrogen supply closer to industrial demand.

The third dimension identified opportunities to incorporate circular economy principles into the green hydrogen value chain through resource reuse, material recovery, by-product valorization, waste utilization, and integration among production processes. Circularity also encompasses water and energy efficiency and the consideration of impacts throughout the life cycle. Connecting hydrogen production with waste recovery, industrial activities, and other economic sectors may support more integrated production systems and reduce resource losses. However, realizing these opportunities depends on technical and economic feasibility, compatible infrastructure, and coordination mechanisms among value chain participants.

From a public policy perspective, the findings indicate the need for integrated planning of the green hydrogen value chain in Brazil. Public authorities should coordinate policies on energy, industry, water resources, logistics, regional development, and environmental

protection to ensure that projects are assessed not only according to their production capacity but also in terms of territorial integration and socioeconomic and environmental effects. Planning should consider the actual availability of renewable electricity and water, transmission infrastructure capacity, storage and transportation alternatives, proximity to consumers, and connections with domestic and international markets. Monitoring mechanisms should also be established to track indicators of energy performance, water consumption, life cycle emissions, resource recovery, and territorial impacts.

For the industrial sector, integrated planning among hydrogen producers, energy suppliers, logistics operators, port facilities, and industrial consumers is recommended. Prior assessment of technological alternatives for storage and transportation, logistics costs, and opportunities for by-product utilization may support more consistent investment decisions. Similarly, circular economy practices should be accompanied by indicators capable of evaluating their outcomes, preventing the use of renewable energy sources from being treated, in isolation, as evidence of sustainability. Cooperation among companies, research institutions, and public authorities may also foster technological development and the identification of solutions suited to the characteristics of each region.

Future research should apply this approach to different Brazilian territories, comparing production areas and industrial centers in terms of infrastructure, logistics flows, water availability, and integration with regional economic activities. Life cycle assessments, techno-economic analyses, and investigations into circularity models applicable to the green hydrogen value chain are also recommended. Comparative studies could further examine the

conditions under which production hubs contribute to regional development, environmental impact reduction, and increased value added in industrial activities.

In conclusion, this study contributes to the analysis of the challenges and prospects of the green hydrogen value chain in Brazil by integrating the dimensions of sustainability, territory, and the circular economy. This approach demonstrates that the contribution of the value chain to the energy transition depends not only on the availability of renewable energy sources but also on territorial planning, infrastructure, resource-use efficiency, production integration, and coordination among public and private stakeholders. Establishing a sustainable green hydrogen value chain therefore requires coordinated technological, industrial, and territorial decisions guided by environmental, economic, and social criteria.

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