

Green Hydrogen in Ceará

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ABSTRACT

The state of Ceará is strategically positioned to become a global leader in green hydrogen (H₂V) production, leveraging its abundant wind and solar resources. Its strategic location, coupled with high solar irradiance and wind availability, enables efficient H₂V production, positioning Ceará as a critical solution for the global transition to sustainable energy sources. Launched in 2021 at the Pecém Industrial and Port Complex (CIPP), the Ceará Green Hydrogen Hub aims to centralize the production, storage, and distribution of H₂V. The hub's implementation plan is divided into three phases: "Formation," "Learning," and "Expansion," designed to drive the state's economy, generate jobs, and contribute to global decarbonization efforts. Ceará has already attracted over 30 national and international companies interested in investing in H₂V production. H₂V production in Ceará represents a dual opportunity: it serves as a critical component in the energy transition while also acting as an economic lever for development. The state is prepared to measure the impacts of economic growth using indicators such as GDP, employment rates, foreign investments, infrastructure development, and environmental and social metrics. Water resource sustainability is crucial for H₂V production, and Ceará is committed to using recovered and recycled water to meet demand. Community engagement is also pivotal to the success of H₂V projects, ensuring local support, promoting sustainable practices, and creating job opportunities. Ceará has established international agreements, such as the Hydrogen Green Corridor with the Netherlands, to facilitate trade and collaboration in the H₂V sector. These partnerships aim to strengthen Ceará's position in the international hydrogen market. H₂V production in Ceará is poised to stimulate economic growth, create jobs, promote environmental sustainability, and position the state as a leader in the global transition to clean energy.

Keywords: Green Hydrogen; Renewable Energy; Sustainability; Economy.

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I. INTRODUCTION

The entire world seeks solutions to reduce greenhouse gases in the atmosphere, the main drivers of climate change. To contain global warming and enable a sustainable future, it is essential to decrease emissions of these gases, particularly CO₂. To this end, it is necessary to replace fossil fuels with renewable energy sources. One of the pathways to facilitate this energy transition and achieve a low-carbon economy is through the use of hydrogen in industrial processes and as an alternative fuel to fossil derivatives (Bezerra, 2021).

According to the same author, green hydrogen, derived from renewable sources such as solar, wind, hydro, and tidal energy, among others, is considered the most promising solution for more sustainable industrial production. However, obtaining hydrogen fuel requires the use of appropriate technologies, which demand substantial energy input (Barroso et al., 2022).

Public initiatives and strategies are being developed to promote its feasibility. Currently, the state of Ceará is supplied by various energy sources. Despite its vast potential for clean energy, Ceará still predominantly produces energy from fossil and non-renewable materials. Given Ceará's capacity to produce clean energy and the current pursuit of investments in the energy sector, new laws and governmental measures have been implemented to encourage the use and production of renewable energies in Ceará, with a particular focus on wind and solar energy matrices (Crispim, 2021).

The state's participation in the Renewable Hydrogen Pact represents a significant milestone for the development of the sector. In this context, it is essential to analyze the public policies implemented by the government of Ceará and their impact on promoting green hydrogen. The general objective of this research is to analyze existing public policies in the state of Ceará that encourage the establishment of green hydrogen generation companies.

The specific objectives are as follows: - To identify the challenges and opportunities for the development of the green hydrogen sector in Ceará; - To evaluate the socioeconomic and environmental impacts of public policies in the context of Ceará's energy transition; - To investigate the role of entities and associations in the development of policies for green hydrogen; - To analyze growth and investment prospects in the renewable energy sector in Ceará.

This scientific article is organized into four sections. The objectives of this research were presented in the first section, the introduction. In the second section, the methodology used for the development of this study was explained. The third section presents the theoretical framework based on contributions from various authors addressing the same topic. Finally, the fourth section provides the concluding remarks of this research.

II. MATERIAL AND METHODS

The study was conducted using a qualitative approach, employing bibliographic and documentary research that involved the analysis of legislation, government programs, sectoral reports, and studies related to the topic. This research methodology was applied to analyze the potential of green hydrogen (H₂ V) as an energy vector and a financial driver for Ceará.

The information and conclusions presented in the article are based on research and data from reliable sources, including the analysis of economic indicators, investments, innovations, and sustainability to evaluate the impact of H₂ V in Ceará.

A case study of the Green Hydrogen Hub in Ceará was examined, where the article analyzes the H₂ V Hub located in the Pecém Industrial and Port Complex (CIPP), exploring its implementation phases, governance model, and key activities. The article builds on existing studies regarding the energy transition, the role of green hydrogen, Ceará's renewable energy potential, and sustainable development initiatives. It also considers critical factors essential for H₂ V production, such as water availability, infrastructure, investment, workforce development, and community engagement.

The article further examines the agreement between Ceará and the Netherlands for the creation of a Green Hydrogen Corridor, highlighting its impact on trade and collaboration within the H₂ V sector. In summary, the article's methodology focuses on research and analysis of existing data to build a robust argument regarding the potential of green hydrogen for Ceará.

III. THEORETICAL FRAMEWORK

3.1 Green Hydrogen as an Energy Vector and Financial Lever for Ceará

The transition to sustainable energy sources is a global imperative, and green hydrogen (H₂ V) emerges as a key solution in this context. The state of Ceará, with its abundant renewable resources, particularly solar and wind energy, is strategically positioned to harness green hydrogen as a fundamental energy vector and a financial lever for economic growth. The ongoing global energy transition reflects a collective effort led by governments, companies, and academic institutions in the pursuit of sustainable models for generating and distributing this vital societal resource: energy.

Green hydrogen plays a critical role in this process, as it is produced through water electrolysis using renewable energy sources, making it a clean and sustainable energy carrier. Here lies one of Ceará's greatest advantages: its geographical positioning, which provides high solar irradiance and wind availability. These conditions facilitate the efficient production of H₂ V, positioning the state as a leader in renewable energy generation in Brazil.

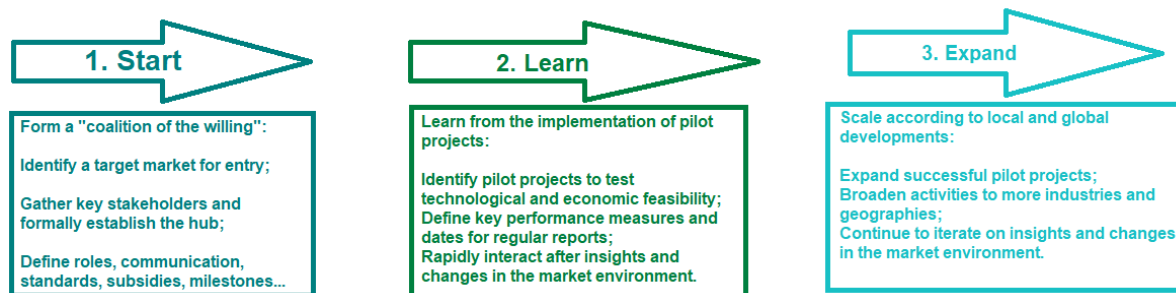
The global shift towards decarbonization demands innovative energy solutions. Green hydrogen can serve as a versatile energy vector, enabling the storage and transportation of energy, thereby addressing the intermittency of renewable sources. This capability is crucial for integrating renewable energy into existing energy systems and supporting the transition to a low-carbon economy.

Ceará possesses a privileged geographical location, as previously mentioned, with abundant sun and wind—key raw materials for H₂ V production. With this vast renewable energy potential, Ceará remains among the national leaders in wind energy production. The state is also energy self-sufficient in onshore solar production and has made significant progress in exploring offshore energy generation. These characteristics have attracted the interest of more than 30 national and international companies willing to invest in green hydrogen production. This influx of investment not only supports the development of the H₂ V sector but also stimulates job creation and economic diversification within the state (Almeida, 2018).

In February 2021, the State Government, in partnership with the Federal University of Ceará (UFC) and the Federation of Industries of Ceará (FIEC), launched the Ceará Green Hydrogen Hub (H₂ V) at the Pecém Industrial and Port Complex (CIPP). This hub centralizes the production, storage, and distribution of green hydrogen, aiming to reduce pollutant gas emissions, boost the state's economy, generate jobs, and contribute to global decarbonization. The action plan for the implementation of the Hub is structured into three phases, as

illustrated in Figure 1, with the objective of establishing the Green Hydrogen Hub and ensuring a clear governance and management model.

Figure 1 – Phases of Green Hydrogen Hub Implementation



Source: Researchers' Data

The establishment of a green hydrogen hub in Ceará is a strategic initiative aimed at coordinating stakeholders and optimizing resources. The initial phase involves forming a coalition of committed stakeholders, which is essential for the successful implementation of the hub and its governance model. This collaborative approach is expected to enhance the state's competitiveness in the green hydrogen market. In the second phase ("Learn"), the hub focuses on implementing projects, initially smaller pilot projects that serve as learning opportunities. The goal of this phase is to progressively achieve higher efficiency through continuous learning. Metrics are monitored, measured, and corrective actions are developed. The expected completion time for this phase is by the end of 2030. The end of this phase does not mean that learning has ceased; on the contrary, it ensures the foundation for investing in larger projects, with more final products and new technological developments, which occurs in the "Expand" phase (Barroso et al., 2022).

For each implementation phase, specific metrics ("KPIs – Key Performance Indicators") must be defined and periodically reviewed to ensure they remain realistic yet sufficiently challenging to guarantee the project's agility and maximum success. These metrics will be defined by the Hub's Strategic Committee, but among the most important are: jobs created, economic impact, volume of hydrogen produced, and number of people trained. Other specific metrics relevant to each segment of the value chain or critical to a particular implementation phase will complement the measurement framework (Barroso et al., 2022).

The following outlines the main activities involving various stakeholders, propagating Ceará's hub both locally and globally, securing international agreements, conducting training, education, R&D initiatives, and facilitating capital access. The implementation and operational timelines of the hub have been developed based on guidelines focused on swift execution and state development. This includes the initial nominations, team assemblies, and the definition of operational and governance models, which will occur in 2024. These will be followed by data collection, supplementary studies, and the planning of key areas/actions, all of which are scheduled for completion by the end of 2025.

The first version of key initiatives (marketing roadshows, training courses, international agreement signings, among others) in each area will take place in the second half of 2025 or the first half of 2026 and will be repeated multiple times over the following years, being refined, updated, and expanded. More sophisticated and/or complex initiatives, such as establishing a startup ecosystem or defining criteria for a green certification label, will occur between 2027 and 2030. By positioning itself as a green hydrogen hub, Ceará can leverage its renewable energy resources to create a sustainable economic model. This includes not only energy production but also the potential for green hydrogen export, generating revenue and increasing the state's economic resilience.

This presents a dual opportunity for the State of Ceará: a critical component of the global energy transition and a significant financial lever for economic development. By capitalizing on its renewable energy potential and fostering collaboration among stakeholders, Ceará can lead the green hydrogen economy, contributing to both local and global sustainability goals (McKinsey & Company, 2021; Ceará, 2023).

Ceará is prepared to measure the impacts of economic growth through various strategies and indicators aligned with its sustainable development goals, particularly in the context of green hydrogen and renewable energy initiatives. Among the main approaches that can be employed are economic indicators, including the Gross Domestic Product (GDP), where an increase in GDP may indicate successful economic activities, particularly in the renewable energy sector. Employment rates are another key measure, as monitoring job creation in the green hydrogen sector and related industries can reflect the positive impact of new investments and projects in Ceará.

Another important aspect is the tracking of foreign and domestic investments by measuring the volume of investments attracted to the green hydrogen sector. This includes monitoring memorandums of understanding (currently totaling 30) signed with companies and the establishment of new projects, which may signal economic

confidence and growth potential. Infrastructure development is another critical approach, evaluated through investments in infrastructure such as renewable energy facilities and transportation networks, which will help assess the economic impact of green hydrogen initiatives.

Additionally, the outcomes of research institutions and local partnerships can provide insights into levels of innovation. Successful R&D efforts can lead to new technologies that drive economic growth. Patents and new technologies are also relevant indicators, as the number of patents filed and new technologies developed in the renewable energy sector can serve as evidence of economic dynamism and growth potential. Environmental and social metrics are equally important, assessed through sustainability evaluations that measure the environmental impacts of economic activities, such as reductions in carbon emissions. These align with global sustainability goals and can enhance Ceará's attractiveness to investors. Quality-of-life indicators, including improved access to clean energy and job opportunities, will provide a holistic view of the economic growth impacts on the community (Costa et al., 2019; Miranda, 2019; Ceará, 2023).

Thus, by employing a combination of economic indicators, investment tracking, innovation metrics, and sustainability assessments, Ceará can effectively measure the impacts of economic growth. These strategies will not only highlight the success of green hydrogen initiatives but also ensure that growth remains sustainable and beneficial to the local population. This comprehensive approach will enable Ceará to adapt and refine its strategies for continuous economic development in the renewable energy sector (Costa et al., 2019; Ceará, 2023).

3.2 Key Considerations for Green Hydrogen Production in Brazil and Ceará

The implementation of green hydrogen production projects in Brazil, particularly in Ceará, involves several critical factors that must be taken into consideration, especially given the state's significant potential for generating renewable energy, primarily from wind and solar sources. These resources are essential for the electrolysis process used to produce green hydrogen, making the state an ideal location for such projects. However, it is necessary to address the availability of water, as ensuring a sustainable and reliable water supply is crucial for the success of these initiatives.

Water is the main input in the electrolysis process, and Ceará has demonstrated efforts to meet this challenge through its Water Reuse Plan, which aims to use treated wastewater, converting up to 1.5 m³/s of residual water into reusable water for hydrogen production. This approach not only conserves freshwater but also helps effectively manage wastewater. There are also water recycling initiatives, such as the Utilitas Pecém Project, which seeks to transform 307 m³/s of residual water into reusable water for the Pecém Port Complex. This initiative highlights the importance of water recycling to ensure a sustainable supply for hydrogen production processes (Fussuma et al., 2024).

As the number of hydrogen production projects increases, it is essential to monitor and manage water demand. Projections indicate that by 2034, the total water demand for these projects may reach approximately 2.14 m³/s. Planning for this demand will be fundamental to ensure that water resources are not overexploited (Cavalcante, 2024).

Collaboration with local water management authorities can support the development of strategies that align hydrogen production needs with the sustainable use of water resources. This includes evaluating the impact of water extraction on local ecosystems and communities (Fussuma et al., 2024).

The electrolysis process itself can be optimized to use less water. Research and development of more efficient electrolysis technologies can help reduce the overall water footprint of hydrogen production (Miranda, 2019).

Community engagement through local education initiatives can promote awareness and encourage involvement in water sustainability efforts. Educating the local population on the importance of water conservation in hydrogen production can foster a sense of ownership and responsibility toward water resources (Fussuma et al., 2024).

By implementing these strategies, the sustainability of water resources during green hydrogen production can be effectively ensured, making the projects both environmentally responsible and socially acceptable.

3.3 The Role of Community Engagement in Green Hydrogen Projects

Community engagement plays a vital role in the successful implementation and sustainability of green hydrogen projects, particularly in regions like Ceará (Ceará, 2022). The support of the local community is essential and has been pursued by involving residents in planning and decision-making processes, helping to build trust and support for hydrogen projects. When local residents feel included, they are more likely to support initiatives that may impact their environment and economy (Ceará, 2022; Fussuma et al., 2024).

Community engagement initiatives can educate residents about the benefits of green hydrogen, including its potential to reduce carbon emissions and create jobs. This knowledge can foster a positive perception of projects and encourage local participation. To ensure the efficiency of these efforts, feedback channels will be established to allow residents to express their concerns and suggestions regarding hydrogen production. Such

feedback can be invaluable for project developers to address potential issues and improve project outcomes (Cavalcante, 2024).

Promoting sustainable practices within the state, alongside community involvement in sustainability efforts such as water conservation and energy efficiency, can enhance the overall impact of hydrogen projects. Local engagement can lead to innovative solutions that align with community values and environmental goals (Costa et al., 2019).

Community involvement can also result in the creation of local jobs and business opportunities related to the hydrogen sector. By fostering local entrepreneurship, projects can contribute to the region's economic development. Collaboration with local organizations, such as universities and industry associations, can further enhance the effectiveness of community engagement efforts. These partnerships can facilitate knowledge sharing and mobilize resources for hydrogen initiatives. A critical aspect of hydrogen production projects is understanding and respecting the local cultural and social dynamics, as this is seen as essential for project success. Community engagement ensures these factors are considered, leading to more culturally sensitive and accepted solutions. The production of green hydrogen (H₂V) in Ceará is expected to bring several significant benefits to the region, including the establishment of a green hydrogen hub designed to export up to one million tons of hydrogen to Europe by 2030. This initiative aims to stimulate economic growth by creating jobs and attracting investments in renewable energy and infrastructure development (Matos; Bitencourt, 2023).

By investing in renewable energy sources, such as solar and wind, Ceará can increase its energy independence. The state has favorable conditions for solar and wind energy production, which are essential for the sustainable production of green hydrogen. The focus on green hydrogen aligns with global efforts to reduce carbon emissions. By utilizing clean energy sources for hydrogen production, Ceará can contribute to environmental sustainability and combat climate change. This initiative also offers opportunities for job creation and workforce development, as the growth of the green hydrogen sector will require a skilled workforce. Programs are being implemented to provide training and qualification, with the aim of preparing approximately 1,300 people for jobs in this emerging field.

Ceará has signed agreements with the Netherlands to create a Green Hydrogen Corridor, facilitating trade and collaboration in the hydrogen sector. This partnership is expected to enhance Ceará's position in the international hydrogen market. The agreement, signed in May 2023 at the Port of Pecém, includes the Port of Rotterdam and the Green Ports Partnership and establishes support from Dutch companies for exporting and investing in Brazil, as well as supporting Brazilian companies with investments and exports to the Netherlands (Matos; Bitencourt, 2023; Cavalcante, 2024).

The production of green hydrogen will require significant investments in infrastructure, particularly in the Pecém Industrial and Port Complex (CIPP). This development will not only support hydrogen production but also improve the region's overall infrastructure (Matos; Bitencourt, 2023). The initiative to produce H₂V and the agreements reached encourage collaboration with neighboring states to enhance renewable energy production, promoting a cooperative approach to energy generation and distribution.

IV. DISCUSSION AND CONCLUSION

The article concludes that Ceará possesses significant potential to become an important producer and exporter of green hydrogen (H₂V), contributing to the global energy transition and fostering the sustainable economic development of the state. The text highlights Ceará's abundant renewable resources, particularly solar and wind energy, as the foundation for the competitive and clean production of H₂V.

The article emphasizes the importance of the Ceará Green Hydrogen Hub, located at the Pecém Industrial and Port Complex (CIPP), as a strategic hub for the production, storage, and distribution of H₂V. The initiative aims to attract investments, create jobs, and promote the decarbonization of the economy.

Key points highlighted include the need to ensure the sustainable availability of water for H₂V production, using recovered and recycled water, monitoring demand, and promoting conservation; the crucial role of community involvement for the success of H₂V projects, ensuring local support, social inclusion, and job creation; and the benefits of H₂V production for Ceará, such as energy independence, reduced carbon emissions, job creation, workforce development, and the attraction of investments.

Additionally, the importance of international partnerships, such as the Green Hydrogen Corridor with the Netherlands, is considered to strengthen Ceará's position in the global H₂V market. The article concludes that, by capitalizing on its renewable energy potential and fostering collaboration among stakeholders, Ceará can lead the green hydrogen economy, contributing to both local and global sustainability goals. H₂V production is presented as a dual opportunity for Ceará: a critical component of the energy transition and a significant financial leverage for economic development.

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