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Ceará, The Federation Of Industries Of The State Of Ceará (FIEC), And Green Hydrogen Production: A Global Benchmark In Energy Transition And Economic Decarbonization

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Abstract:
Background*: Global warming is already a reality on the planet, with climate change and extreme weather events occurring with unprecedented frequency. One of the solutions lies in the decarbonization of the economy through the use of green hydrogen, which requires renewable energy sources. Ceará has the potential to become a provider of this global solution.*
Materials and Methods: *The chosen methodology is characterized by a qualitative approach. The research methods utilized were bibliographic and documentary. The general objective is to explain how the State of Ceará has become a global reference in the production of green hydrogen, contributing to the energy transition and the decarbonization of the global economy.*
Results*: The research confirms that the geographic conditions and the role played by FIEC position the State as a potential supplier of the fuel of the future.*
Conclusion*: Ceará's advancements in green hydrogen production highlight its strategic importance in addressing global energy challenges and promoting sustainable development.*
Key Word: *Decarbonization; Renewable energies; Green hydrogen; Global solution; Climate change.*

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I. Introduction

Global warming is already a reality on the planet. As a consequence of climate change, extreme events have been observed to occur with unprecedented frequency, directly affecting the socioeconomic lives of millions of people. One potential solution is to reduce the production of fossil fuels, intensify the energy transition by increasing the use of renewable energies, and decarbonize the global economy to mitigate the environmental disasters that nature has demonstrated across all continents[1].

At a global scale, part of the solution lies in the production of green hydrogen, which necessarily relies on renewable energy sources such as photovoltaic solar and wind energy. Could the State of Ceará serve as a provider of this global solution in this race against time? The outlook is highly promising, and progress is already underway.

Regarding the methodology, a qualitative approach was chosen. For the means of investigation, the study was bibliographic and documentary, conducted through analyses of national and international publications, reports, scientific articles, and online sources. From the consultation and consolidation of these materials, it was possible to identify the most relevant issues related to the topic.

Thus, the general objective of this study is to explain how the State of Ceará has become a global reference in the production of green hydrogen, contributing to the energy transition and the decarbonization of the global economy. The specific objectives established are as follows: - To characterize how the physiographic conditions of the State of Ceará provide excellent conditions for wind and solar energy production, which are the foundations for green hydrogen; - To understand the causes and reasons that have led the international community toward energy transition and the decarbonization of the economy; - To present the main contexts related to green hydrogen, considered the fuel of the future; - To identify the actions and initiatives of the Federation of Industries of the State of Ceará (FIEC) as a key player in the global green hydrogen value chain.

This article is structured into four sections. The first is the introduction, which outlines the objectives of this research. The second is the methodology, which details the procedures adopted to develop this study. The third is the theoretical framework, where a theoretical discussion is presented to support the research with the quality of the contributions collected. Finally, the fourth section presents the concluding remarks.

II. Material And Methods

Leveraging the geographic conditions of the State of Ceará and the actions and initiatives promoted by the Federation of Industries of the State of Ceará (FIEC), this study focuses on the measures that explain how Ceará holds the potential to become a global actor in the energy transition through green hydrogen production.
A qualitative approach was chosen to explore the anticipated outcomes. Regarding the qualitative approach, González (2020, p. 03) emphasizes that: "In Qualitative Research, the Epistemological Stance is highlighted and assumed by researchers, who therefore undertake cognitive commitments to the quality of the research[2]."

Research Methods

The study employed bibliographic and documentary research, which involved the following techniques: 1. Collection of relevant bibliographic and documentary materials; 2. Selection of pertinent bibliographies and documents; 3. Analytical reading of the selected materials; 4. Notetaking and indexing; 5. Critical analysis and consolidation of the research questions.

Carvalho (2022, p. 13) highlights the importance of bibliographic research: "Bibliographic research is an essential part of scientific work as it contextualizes the current research landscape, identifies conceptual inconsistencies, and stimulates new studies, all through the summarization and synthesis of existing works[3]."

The bibliographic research included publications, scientific articles from journals, and documents from academic institutions and credible online sources. Documentary research involved consulting government documents, as well as national and international reports.

Data Analysis

By integrating and consolidating these materials, the study identified and critically analyzed the key issues related to the topic, ensuring a comprehensive understanding of Ceará's potential role in the global energy transition through green hydrogen production.

III. Theoretical Framework

This theoretical framework is organized into four subsections. The first addresses the physiographic conditions of the State of Ceará. The second explores the causes and reasons behind the energy transition and the decarbonization of the economy. The third presents an overview of green hydrogen. Finally, the fourth examines the actions and initiatives of the Federation of Industries of the State of Ceará (FIEC) within the global green hydrogen value chain.

Physiographic Conditions of the State of Ceará

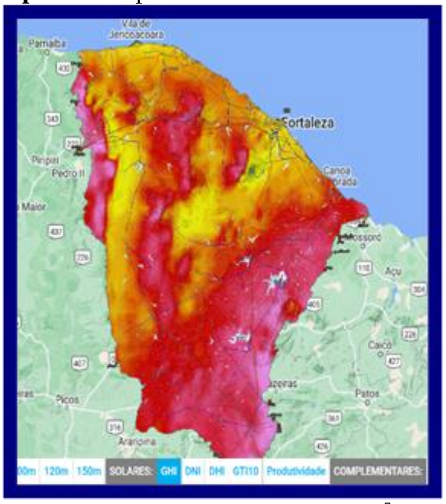
Physiographic factors are typically divided into several components: area characteristics (surface, shape, position, and boundaries), geology, relief, hydrography, coastline, climate, and vegetation [4]. In this study, the analysis focused on Ceará's position, coastline, and climate (temperature and winds).

According to Mattos (1975, p. 18), "the geographical position of a region is evaluated based on latitude, proximity to or distance from the sea, altitude (plain, plateau, or mountains), and its relative position to neighboring countries[5]".

Specifically, Ceará is situated in the northeastern part of Brazil, at a latitude of 4°46'30" South. Due to its proximity to the Equator, the solar rays strike its surface almost perpendicularly, resulting in higher temperatures compared to regions at higher latitudes.

These conditions significantly enhance the potential for the exploitation of photovoltaic solar energy. The Wind and Solar Atlas of Ceará (Map 1) confirms the extent to which Ceará's geographic position enables economic exploitation of solar energy, yielding a photovoltaic potential of 643 GW[6].

Map 1: Solar potential of the State of Ceará.



Source: Atlas Eólico e Solar do Ceará [7]

In this context, the "solar belt" was defined by the National Institute for Space Research (INPE), delineating a region that extends from the Northeast to the Pantanal. The best irradiation rates are found between the semi-arid regions of Bahia and parts of Minas Gerais. As shown in Map 2, Ceará is entirely within the Brazilian solar belt.

Map 2: Solar Radiation in Brazil.

Source: Portal Solar[8]

Situated in the region known as the Northeastern Salient, Ceará's strategic position shortens distances to the European continent and places the state near important maritime export routes and consumer markets[7].

This advantageous location facilitates access to major international trade flows involving products, goods, and services. Regarding maritime proximity, the state is bordered by the Atlantic Ocean, a body of water of great economic importance in the globalized world, which enhances overseas trade exchange opportunities[5,9,10,11].

Additionally, the continental shelf along Ceará's coastline provides favorable conditions for land-sea integration, such as optimal sites for the establishment and construction of ports, including the Port of Pecém, which hosts the Pecém Industrial and Port Complex (CIPP). The Port of Pecém's infrastructure has become essential for economic, social, and technological development, significantly boosting Ceará's export portfolio.

Regarding altitude, Mattos (1975, p. 20) emphasizes that "altitudes create favorable or unfavorable conditions for socioeconomic development, with plains always facilitating human circulation and land exploitation[5]." In Ceará's case, coastal plains in the northern region stretch along the Atlantic, with elevations ranging from 30 to 100 meters, increasing progressively towards the interior of the state. Unsurprisingly, the combination of geographic position and wind conditions in Ceará's plains has enabled the installation and operation of numerous wind farms (Map 3).

The location of these wind farms on coastal plains facilitates construction, as well as subsequent operation and maintenance (O&M). Among the factors that favor Ceará's wind energy landscape are the natural geographical advantages, which grant substantial generation potential, alongside the complementarities with the already established national energy systems, particularly photovoltaic and hydroelectric energy[12].

Map 3: Location of Wind Farms in Ceará.

Source: Revista Litoral Leste (2014)[13]

Wind energy is regarded as the cleanest energy source globally and an excellent renewable energy alternative, as it does not pollute the environment, contribute to the greenhouse effect, or encroach on agricultural land[21]. According to the Brazilian Wind Energy Association (ABEEólica), the Brazilian Northeast accounts for 85% of the nation's total electricity generation from wind energy. Out of 534 wind farms across Brazil, 430 are located in the Northeast. The five states with the highest generation in 2022 were Bahia (24.17 TWh), Rio Grande do Norte (23.20 TWh), Piauí (10.29 TWh), Ceará (7.06 TWh), and Rio Grande do Sul (5.37 TWh)[14].

The region benefits from a continuous flow of trade winds, further amplified by mesoscale phenomena like sea breezes, making it rich in energy potential. Ceará currently ranks third in the number of wind farms in Brazil, with renewable energy dominating its energy matrix. Consequently, numerous studies advocate for the installation of wind farms based on statistical, technical, and financial feasibility criteria. One such conclusion was drawn from a case study conducted by Silva et al. (2020, p. 237), which employed the Weibull probability distribution to estimate energy potential through wind speed analysis [7,15,16].

The synergy between high solar irradiation and coastal winds positions Ceará as a potential producer of green hydrogen (H_2V). Its competitive production costs could establish it as a global player in the hydrogen economy, given its renewable energy-based electricity matrix. These characteristics align with the International Renewable Energy Agency's (IRENA) report, which asserts that H_2V production will be more economically viable in regions with abundant renewable resources, available land, water access, and the ability to transport hydrogen to major importing countries[17].

Studies by the Brazilian Development Bank (BNDES) indicate that the primary factors influencing H_2V production costs include the acquisition cost of renewable electricity used in the production process[18].

Ceará's geographic position within the solar belt, combined with its climatic conditions (temperature and wind), underscores its promising potential for both solar photovoltaic and wind energy. This complementary energy profile offers attractive operational, logistical, and commercial advantages, making the state a competitive renewable energy supplier to Europe compared to other producing countries.

As Oliveira (2022, p. 8) observes, "Europe is increasingly focused on using hydrogen to decarbonize industrial sectors and heavy transportation (buses and trucks)[19]." Geopolitical Perspectives and the H_2V Value Chain in Ceará from a geopolitical perspective, proposed criteria for assessing a region's potential or power, including geographic size and position, population, natural resources, industrial capacities, science and technology, military capacity, and internal cohesion[9]. Applying Mattos's criteria to Ceará's H_2V value chain projects (in terms of production and export potential), the state's scenario can be outlined as shown in Table 1 below:

Table 1: Assessment of Ceará's Potential in the H_2V Value Chain

Geopolitical Assessment Criteria according to Meira Mattos' Methodology	Favorable Factors
Dimension	The territorial dimensions favor the implementation of the H_2V value chain in Ceará.
Geographical Position	Privileged and strategic location in the Northeastern Promontory, enabling easy access to maritime routes and trade exchanges via the Atlantic to Europe.
Population	Allows for the training of specialized human resources for the benefit of the H_2V value chain.
Natural Resources	High potential for solar photovoltaic and wind energy generation, reducing production costs and increasing competitive advantages.
Industrial Capacities	Industrial park installed in the CIPP.
ST&I	R&D projects underway by the National Service for Industrial Learning (SENAI).

Source: Adapted from Mattos (1977)[9] (Modified by the Authors)

Once again, it is evident that Ceará benefits from several favorable factors for the establishment and development of the hydrogen economy, enabling it to transform its circumstantial potential into economic and energy power. From a geopolitical perspective, Table 2 summarizes Ceará's advantages based on its physiographic aspects.

Table 2: Summary Table

Physiographic Aspect	Geographic Aspect	Political, Economic, and/or Energy Activity	Consideration
Position	Low latitude	Solar energy production	- Catalyst for Ceará's socioeconomic development as a result of H_2V production and export.
	Altitude (plain)	Wind energy production	
	Maritime influence	Foreign trade	
Coastal	Maritime influence	Port construction	
Climate	Wind	Wind energy production	
	Solar belt (semi-arid)	Solar photovoltaic energy production	

Source: Researcher Data

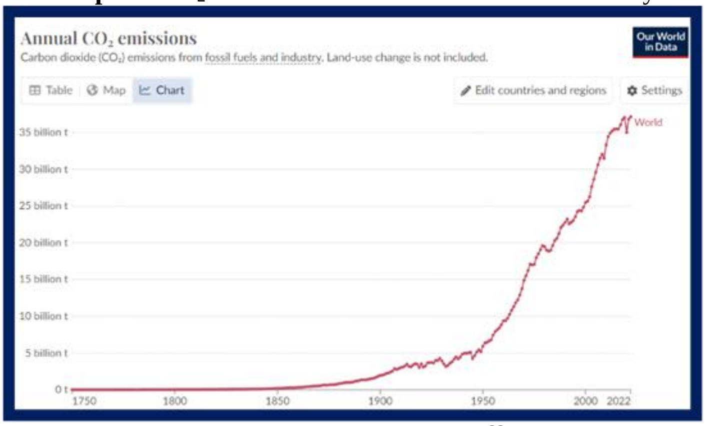
Causes and Reasons for Energy Transition and Decarbonization of the Economy

The ecosystems that comprise the biosphere are highly sensitive to human-induced disruptions. Environmental pollution and the depletion of natural resources have been topics of extensive research, as the rapid pace of environmental degradation threatens the regeneration and recovery capacities of these systems[20].

The "greenhouse effect" is a physical process that stabilizes the Earth's temperature, enabling life to thrive in terrestrial ecosystems. According to an article from National Geographic, French physicist Jean Baptiste Joseph Fourier calculated in 1824 that the Earth would be approximately 15.5 ºC cooler without the atmosphere (greenhouse effect), making life on the planet more challenging. In 1896, Swedish scientist Svante August Arrhenius became the first to recognize that burning billions of tons of oil, coal, and gas would significantly increase atmospheric CO_2, thereby contributing to global warming[21].

The graph below illustrates that prior to the First Industrial Revolution (1760–1850), CO_2 emissions were extremely low and remained relatively steady until the mid-20th century. By 1950, however, the globalized world was emitting 6 billion tons of CO_2 from the combustion of fossil fuels. From that point onward, emissions increased dramatically, reaching 37 billion tons by 2022.

Graph 1: CO_2 Emissions from Fossil Fuels and Industry



Source: Our World in Data[22]

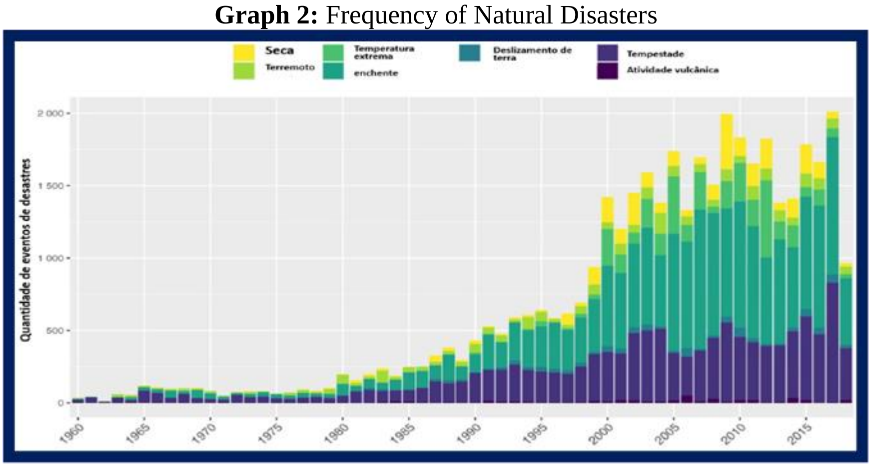
The rapid and disruptive industrial development led to increased emissions of polluting gases, prompting the international community to launch a global effort to mitigate their effects through an energy transition capable of alleviating global warming and its consequences. In the 1970s, it became evident that excessive consumption of natural resources and the overuse of fossil energy were causing significant environmental degradation, harming people's quality of life.

Thus, global warming is a phenomenon in which heat is trapped by the Earth's atmosphere, intensified by the presence of pollutants[7], primarily as a result of excessive burning of fossil fuels (CO_2), which increases their concentration in the atmosphere. These are, therefore, the greenhouse gases (GHGs).

The emergence of numerous environmental problems and various climate events are nature's responses to the limits reached by economic activities dependent on the intensive use of fossil fuels. If the situation is not reversed, it could push the planet further away from achieving a sustainable society. Extreme natural events have become increasingly frequent, such as rising sea levels, widespread droughts, shifts in climate patterns, melting glaciers, and the rise in global average temperatures[23].

These events were highlighted in the 2007 report by the Intergovernmental Panel on Climate Change (IPCC)[21]. Other studies point to an increase in natural disasters worldwide, showing a direct relationship between GHG emissions and global temperature rise (Graph 2).

Graph 2: Frequency of Natural Disasters



Source: XII Encontro Nacional da Associação Brasileira de Estudos de Defesas (ENABED).

Droughts, floods, storms, and extreme temperatures are the most evident cases in recent decades. "To address these climatic events, national and international organizations are tirelessly seeking to establish environmental awareness, aiming to reconcile economic activities without compromising natural resources for future generations[20]"

Hence, the pressing need to seek alternative energy sources that are cleaner and ecologically sustainable, in contrast to fossil fuels derived from petroleum. These findings are presented in the 19th Edition of the 2024 Global Risks Report, published by the World Economic Forum (WEF), which consolidates various surveys and questionnaires directed to 1,500 global leaders and over 200 thematic experts. One of the conclusions was the recognition of a world plagued by a dangerous climate crisis[24].

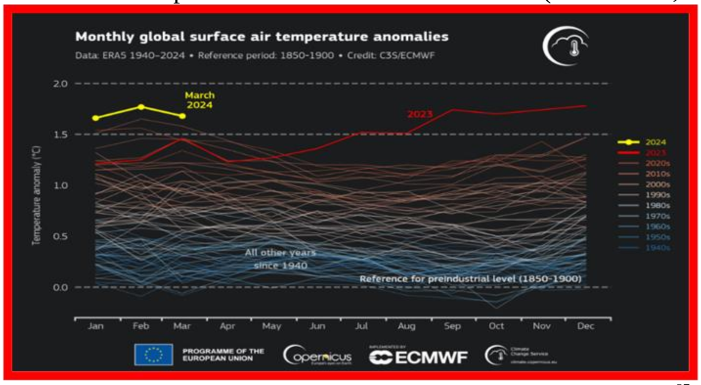
In this report, environmental concerns were highlighted by two-thirds (66%) of the respondents, who classified extreme weather conditions as the most probable risk for a global-scale crisis in 2024. When asked about potential risks in the next two years and in ten years, the results were as follows: In the short term, extreme weather events ranked as the number two concern, and pollution ranked tenth. However, in the long term, extreme weather events took the first position, biodiversity loss came in third, resource scarcity was in fourth, and pollution remained in tenth place[24].

These findings reinforce the urgent need for countries to implement the energy transition and decarbonization of their economies to help mitigate the effects of global warming and prevent global crises from emerging. The National Institute of Meteorology (INMET) published the "Global Climate State" report by the World Meteorological Organization (WMO), stating that "the year 2023 is already considered the hottest in 174 years of meteorological measurements"[25,26].

Among other surprising and concerning data, the report presented the following: The global average temperature over the last ten years is 1.19 ± 0.12°C above the 1850-1900 average (the hottest ten-year period ever recorded). The concentrations of the three main greenhouse gases (carbon dioxide, methane, and nitrous oxide) reached record levels in 2022. Ocean heat reached its highest level in 2022 compared to the available data of the last 65 years. In 2023, the average sea level surpassed previous years, reflecting the melting of glaciers and ice sheets[26].

The Copernicus Climate Observatory of the European Commission, in its report, pointed out that in March 2024, the average temperatures were 1.68°C higher than in a March from the pre-industrial era (1850-1900). In the last twelve months, global temperatures were 1.58°C higher than in the pre-industrial era, exceeding the 1.5°C limit established by the Paris Agreement. The temperature of the oceans has been warmer than ever for over a year, setting a new historical record with an average surface temperature of 21.07°C[27].

Graph 3: Global Air Temperature Anomalies at the Surface (1850–1900; 1940-2024)

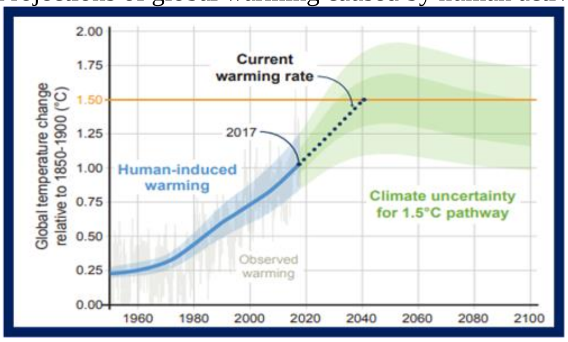


Source: Copernicus Climate Observatory of the European Commission (2024)[27].

In Graph 3, the year 2024 is highlighted in bold yellow, 2023 in bold red, and all other years are represented with thin, shaded lines according to the decade, from blue (the 1940s) to dark red (the 2020s). The data provided suggests a potential increase in damage to marine ecosystems, leading to more humidity in the atmosphere, higher wind speeds, and stronger rainfall.

According to the Intergovernmental Panel on Climate Change (IPCC), human-induced warming reached approximately 1°C above pre-industrial levels by 2017. In Graph 4, "if current economic activities based on fossil fuels continue, global temperatures will reach 1.5°C by around 2040" (IPCC, 2022, p. 82). These are situations that require action from governments, institutions, and the general population.

Graph 4: Projections of global warming caused by human activityhumana



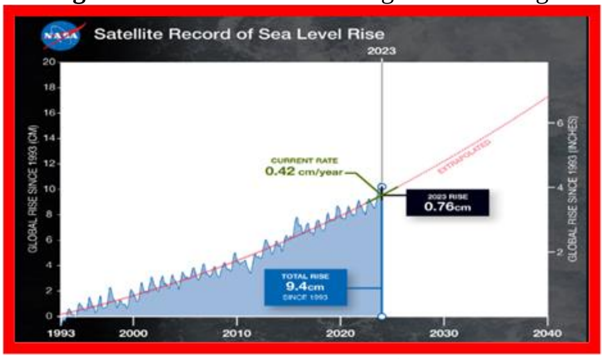
Source: IPCC (2022, p. 82).

Flooding in coastal areas, the increased spread of diseases (due to high temperatures), difficulty in accessing potable water sources, reduced agricultural production (impacted by adverse and extreme weather events), and rising food prices, among others, are examples of the effects that various cities have been facing, leading to disastrous socio-economic impacts[28].

In March 2024, the National Aeronautics and Space Administration (NASA) published an article titled, "Too Hot to Handle: How Climate Change Could Make Some Places Uninhabitable[29]". Based on satellite data, the agency estimated that certain regions of the world would become uninhabitable due to global warming within 30 to 50 years.

According to the climate models used, certain areas could exceed current temperature levels, indicating that the most vulnerable regions would include South Asia, the Persian Gulf, and the Red Sea around 2050, and East China, parts of Southeast Asia, and Brazil by 2070. Also in 2024, NASA released scientific data revealing that, by 2050, sea levels could rise by up to 20 centimeters, driven by climate change. Figure 5 shows the average sea level from 1993 to 2023 in blue. The continuous red line indicates the trajectory of this increase (1993 to 2023), which has more than doubled over the past three decades. The dashed red line projects future sea-level rise[29].

Figure 5: Sea level rise due to global warming.



Source: NASA (2024)[29].

Scientists from the British Antarctic Survey concluded that the melting recorded in Antarctica in 2023 would have been "extremely unlikely" without climate change, with the maximum extent of sea ice coverage decreasing by two million square kilometers. Additionally, studies indicated that climate change has quadrupled the likelihood of such large and rapid melting events[30].

The simultaneous convergence of the aforementioned effects has the potential to decisively affect countries, impacting millions of people socially and economically. Oliveira (2024) summarizes this scenario by stating that: These climate crisis-related evidences present an imperative to all rational beings inhabiting the planet: the energy transition must be intensified, or the minimum conditions for habitation will be lost in a short period of time. In Germany, in response to the urgency of the energy transition, the government updated the National Security Strategy (NSS) in 2023, emphasizing its commitment to combating the climate crisis, among other challenges[31,32].

Specifically, regarding climate, it stated: The climate crisis threatens the foundations of our life and economy. It already has significant repercussions on security policy. We will no longer be able to fully prevent the consequences of this crisis, but we will be able to mitigate them[32].

Green Hydrogen

The search for alternative energy sources to fossil fuels is not recent. Historically, in 1923, John Burdon Sanderson Haldane was the first to describe the concepts of the hydrogen economy, predicting that in 400 years, the energy issue in England would be solved with hydrogen use. Only in 1990, "the first pilot $H^{2}V$ plant, using solar energy, was installed by Solar-Wasserstof-Bayern"[33].

As Holanda (2018, p. 34) discusses, food production and pollution, for example, are directly related to energy issues, as more and more energy is required to produce food; however, most available energy sources are polluting and responsible for global warming[34]. He then asks, "Who will replace oil?" The Russia-Ukraine war has compromised the energy security of European economies, bringing massive instability in fossil fuel prices. With high dependence on Russian fuels, the European Union economies have been seeking short-, medium-, and long-term solutions to reduce energy supply dependence[35]

Hydrogen, considered the pillar of the global energy transformation, holds significant importance in transition strategies in various countries, especially for providing an alternative in highly carbonized sectors[19].

"This position aligns with the United Nations High-Level Political Forum report, which identifies H_2V as a key solution for hard-to-decarbonize sectors"[33].

"Among its main advantages is the decarbonization of sectors such as petrochemicals, steel, iron, and fertilizers. For this reason, global production is expected to grow exponentially in the coming years, with investment figures that could reach 500 billion euros by 2030"[36].

Hence, there is strong advocacy in international forums regarding the advantages of H_2V in addressing climate issues. "However, achieving this goal presents a huge challenge, as its production is still relatively expensive compared to other methods used to obtain it"[37].

The International Hydrogen Landscape

According to the International Renewable Energy Agency (IRENA), it is likely that hydrogen will influence the changing geography of global trade. With the decreasing costs of renewable energy, the emerging geopolitical map is expected to show increasing regionalization in energy relations. The International Energy Agency (IEA) projects that production will rise from 90 million tons (2020) to over 200 million tons (2030).

Estimates from the Hydrogen Council (2023) indicate that Brazil has the potential to become a leading player, with the global market expected to reach US$ 2.5 trillion by 2050, representing about 20% of global energy demand[39,40].

Berger (2023) points out that European governments have set decarbonization targets, developing ambitious strategies and goals[36]. By 2030, it is believed that Europe will stand out with H_2V projects located in areas with access to solar or wind energy. Studies published by the World Energy Council (WEC) suggest that each country tends to adopt its own energy policies. However, there is a global consensus: decarbonizing the economy is the main reason for investing in the hydrogen supply chain, particularly in the heavy-duty and long-distance transport industry, such as buses and trucks[41].

As European hydrogen production falls short of its needs, "a solution would be the importation from countries where hydrogen could be produced more economically and on a larger scale, such as in the Middle East, North Africa, and Latin America"[41]. Bezerra (2023, p. 13) highlighted that "many European countries will not be able to implement the energy transition to achieve a low-carbon economy without resorting to the import of large volumes of clean and renewable energy."[37]

"This same conclusion is echoed by the Port of Rotterdam, which states that importing H_2V will be essential for Europe, as consumption on the continent exceeds its production[42]." Therefore, Ceará's significant opportunity lies in being the key player in meeting this European demand. Studies indicate that Germany may become an importer of liquid hydrogen, given its search for suppliers to ensure its domestic consumption. In fact, it is working to consolidate a global atlas of potential countries, enabling future import agreements[32,41].

Thus, the need for international cooperation emerges as a strategic advantage to strengthen hydrogen in the international market, which aligns with BNDES studies (2022), indicating that for hydrogen to fulfill its crucial role as a decarbonization vector, there would need to be a global increase in production capacity. On one hand, Ceará offers advantages such as the availability of renewable resources at competitive prices, and on the other, there is the demand from Germany, which has partnered with several countries, including Ceará, to develop cooperation activities aimed at purchasing H_2V[18,32,43].

Ceará's opportunity arises precisely from Europe's investments in H2V, which would translate into a significant opportunity for the state's export agenda. Since the EU cannot produce hydrogen in the necessary quantities, the solution would be to prospect international markets for countries capable of production and export, having access to solar and wind energy[19].

The development of hydrogen on a large scale has the potential to create a new industrial sector for high-tech equipment manufacturing. "Regional supply chains for manufacturing equipment (such as electrolyzers and fuel cells) could create opportunities and jobs beyond the major economies, according to the IEA (2021, p. 9).[44]"

"In 2021, prospective scenarios were developed by the German Cooperation Agency (GIZ), assessing the potential hydrogen import demand for the EU and Germany for the years 2030 and 2050, as shown in the following Table 3[19,32]:

Table 3: Scenarios for Hydrogen Import Demand in Germany and the European Union

Parameter	Region	2030		2050	
		Scenario A	Scenario B	Scenario A	Scenario B
Demand for H_2 (TWh)	Germany	4	20	250	800
	European Union	30	140	800	2250

Source: Instituto Fraunhofer (2022)

The considerations outlined above align with the decisions made by the government in its National Security Strategy, p. 8), which stated:

Containing the climate crisis and addressing its repercussions is one of the most fundamental and urgent tasks of this century. A drastic reduction in pollutant emissions on a global scale is imperative. At the same time, a global, sustainable, green, and socially just transformation presents significant opportunities [...][32].

The aforementioned data corroborate Germany's decision to launch the H_2Global Foundation initiative in June 2021[32], aimed at fostering the national green hydrogen (H2V) industry and promoting growth in the global market. According to BNDES (2022, p. 78), "the initiative aims to reduce dependence on fossil energy resources by replacing them with hydrogen, acquiring hydrogen production from exporting countries[18]."

Another German initiative highlighted by Castro et al. (2023, p. 108) was the launch of the "National Hydrogen Strategy," an extensive industrial policy aimed at developing the necessary long-term infrastructure[43]. Oliveira (2024, p. 36) noted that "the vision was to establish an action plan for the hydrogen value chain.[31]" Thus, the estimates above would reflect the international hydrogen market for Europe and specifically for Germany, allowing us to conclude the relevance of CIPP in meeting European and German demands regarding decarbonization[32]. According to ENS (2023), reducing dependencies on raw material and energy supply through diversified supply relationships ensures the availability of critical raw materials[32].

National Hydrogen Landscape

"Brazil has positioned hydrogen as an energy solution to fulfill its international commitment to carbon neutrality by 2050"[45]. In line with this, the report "Hydrogen Market Update in Latin America" indicates that "Brazil is poised to take a prominent place in the global market and become one of the leading exporters of this fuel due to its abundance of renewable energy"[46].

Oliveira (2022, p. 6) clarifies that "Brazil has a strong potential to become a major hydrogen exporter due to its excellent climatic conditions favorable for generating electricity from wind, solar, and hydro sources[19]." Simultaneously, Santos et al. (2022, p. 13) point out that "Brazil has a significant opportunity to play a relevant international role by offering H_2V at lower prices and in large quantities, facilitating access to external markets in Europe."[33] Other studies suggest that H_2V production represents an opportunity for sustainable socioeconomic development in the Northeast region due to low generation costs, thus enhancing H_2V's competitiveness[19].

Brazil possesses solar energy potential comparable to that of desert countries and is also one of the best locations globally for wind energy production[47]. Furthermore, according to Oliveira (2022), the Northeast region is positioning itself as a production hub due to its high potential for wind and solar energy generation and its geographically well-located ports concerning major European markets, particularly highlighting Ceará as having the highest number of announced H2V projects in Brazil[19]. In May 2023, CNI launched the "Industry Recovery Plan: A new strategy focused on innovation, decarbonization, social inclusion, and sustainable growth" (CNI, 2023a).

"Mission 1: Decarbonization" is one of the solutions aimed at combating global warming and reducing greenhouse gas emissions through the development of technologies related to hydrogen, which is playing an increasingly important role in the international arena.

Also in 2023, CNI released the "Strategic Map of Industry 2023-2032: The Path to New Industry," which states that industrial decarbonization would promote better conditions for attracting investments and generating new business opportunities (CNI, 2023b).

In 2024, the Brazilian government launched the "Action Plan for Neoindustrialization 2024-2026," presenting key actions for New Industry Brazil (NIB) designed to facilitate "economic and social transformations aimed at overcoming barriers to Brazilian development" (Brazil, 2024, p. 6).

Similar to the Industry Recovery Plan (CNI, 2023a), NIB includes a specific chapter focused on energy transition: Mission 5 ("Bioeconomy, decarbonization, and energy transition and security to ensure resources for future generations"). In this chapter, hydrogen is emphasized in Brazil's proposed actions, including developing technologies aimed at low-carbon hydrogen and prioritizing financing and innovation credits (MDIC, 2024), aligning with IEA's assertion that efforts toward decarbonization will increasingly rely on technologies that are not yet available[44].

According to Pereira (2024), Brazil's electricity matrix is highly renewable because a significant portion of electricity generated comes from hydropower plants. Wind and solar energy are also growing significantly, contributing to maintaining a predominantly renewable electricity matrix.

Ceará plays a crucial role regarding H_2V in this context by aligning with IEA's report ("Hydrogen in Latin America: From Short-Term Opportunities to Large-Scale Deployment"), which stated: "To have an impact on clean energy transitions in Latin America, end-use sectors must also benefit from the region's competitive advantages in producing such fuel to find opportunities and create jobs in a zero-emissions scenario"[44].

Attention was drawn when the National Energy Policy Council (CNPE) identified "hydrogen as one of the priority topics for research and development aimed at resource application"[52].

This statement followed the National Energy Plan (PNE) for 2050 issued in 2020 when hydrogen was identified as a technology of interest within the context of decarbonizing Brazil's electricity matrix[52]. A year later, Brazil established a strategy for actions related to developing a hydrogen economy through the National Hydrogen Program (PNH_2), overseen by the Ministry of Mines and Energy (MME). As highlighted by the Triennial Work Plan for 2023-2025[45], competitive advantages were emphasized due to installing hydrogen production plants within port complexes (hubs) that also include industrial plants—a conclusion similarly presented by Vasileva (2023)[46].

The understanding is that within a port complex would combine several strategic factors necessary for developing the H_2V chain—such as logistics for exportation and proximity to industrial hubs and renewable energy sources used in electrolysis (hydrogen synthesis)[19].

This strategy is believed to be crucial for making hydrogen economy viable with the goal of fostering investments in energy chain infrastructure. In Brazil, one such port complex is Pecém (CE). "The perspective would be to consolidate low-emission hydrogen hubs in Brazil by 2035 with the aim of catalyzing development and production while integrating necessary infrastructures from production stages through storage, transportation, and consumption"[45].

IRENA also points out in an article titled "The Geopolitics of Energy Transformation: The Hydrogen Factor" that countries with abundant low-cost renewable energy could become global producers of H2V with geoeconomic and geopolitical consequences given their competitiveness and economic feasibility when producing in locations combining abundant renewable resources with space for solar or wind parks along with access to water while being able to export to major demand centers[17]. Ceará reemerges prominently within this competitive landscape.

The Perspective of Ceará in the Hydrogen Economy

In the state of Ceará, the integration and collaboration among various stakeholders in the hydrogen energy and economic chain are evident in the Triennial Work Plan 2023-2025 through the Thematic Chambers. This structure facilitates inter-institutional relationships for the effective implementation of actions related to climate change (production and use of low-carbon hydrogen)[45].

Raccichini, Contardi, and Ristuccia (2022, p. 3) provided an overview of strategies and market issues related to hydrogen in Brazil, emphasizing Ceará as the "First Green Hydrogen Valley in Brazil,"[48] due to its key strategic factors, such as renewable energy sources and the strategic geographical location of the Pecém Industrial and Port Complex (CIPP). Anticipating the Triennial Work Plan by 14 years, Ceará launched its Hydrogen Hub in 2021.

The Federation of Industries of Ceará (FIEC), the State Government, and the Federal University of Ceará (UFC) signed a memorandum of understanding for the construction of a hydrogen production facility at CIPP[37]. To illustrate the magnitude of this agreement, the World Bank and the Ministry of Development, Industry, Commerce, and Services (MDIC) financed the necessary infrastructure for developing the hydrogen hub at Pecém Port with $100 million[46].

These funds reflect studies conducted by McKinsey & Company, which indicate that Brazil's energy matrix is composed of 85% renewable energy, suggesting that investments for national H_2V production could leverage the existing power grid since 70% of hydrogen production costs are attributed to energy expenses[49]. Not coincidentally, in May 2023, the governments of Ceará and the Netherlands established a maritime corridor between Pecém and Rotterdam, creating a shipping route for H_2V to Europe[46].

This partnership is considered strategic as Rotterdam is well-positioned in the European market, serving as a port complex that combines H_2V production and consumption with infrastructure for distribution to other European countries, import terminals, and electrolyzers [19].

For Rotterdam's administration, the goal of this partnership is to strengthen bilateral cooperation and promote initiatives for port development and energy-related projects involving offshore wind energy and H_2V production. Notably, demand for H2V from Rotterdam to Germany could reach up to 20 million tons per year by 2050, with 18 million tons expected to come from imports[32,50].

The port's statistics are impressive: "considered the best port infrastructure in Europe, recognized as the largest in Europe, providing access to a market of 440 million consumers and generating 565,000 jobs while accommodating 30,000 ships annually"[42].

During the World Hydrogen Summit held in Rotterdam in 2022, it was announced that 4.6 million tons of H2V would be distributed to Europe via Rotterdam Port by 2030—4 million tons imported while the remainder would be produced at the port itself[19].

From Ceará's perspective, according to Figueirêdo (2023), with an estimated production of 1.3 million tons of hydrogen per year by 2030, CIPP could potentially meet 25% of Rotterdam's import demand. A competitive advantage of the Hydrogen Hub (CIPP) would also be its designation as a free zone (Export

Processing Zone), providing differentiated tax incentives (Table 4)[50]. The benefits granted to established companies are assured for a period of up to twenty years.

Table 4: CEARÁ EPZ (Tax Benefits)

Entity	Tax Benefits
Federal	- Applicable to the acquisition of goods, inputs, and services from the National Market. Suspension of: IPI, COFINS, and PIS/PASEP. - Applicable to the acquisition of goods, inputs, and services from the Foreign Market. Suspension of: II, AFRMM, IPI, COFINS Importation, and PIS/PASEP Importation.
Regional	- Reduction of up to 75% of the Corporate Income Tax (IRPJ) (SUDENE).
State	- Exemption of ICMS applicable to goods and merchandise used in the industrialization process of products to be exported; - Exemption of ICMS applicable to intermunicipal and interstate transportation services; - Exemption of ICMS in the differential of rates on interstate acquisitions of goods intended for fixed assets.
Municipal	- Possibility of ISS reduction to up to 2%.

Source: Technological Park of UFC. Adaptation by the author.

As industries operate with tax, exchange rate, and administrative benefits[7], the conditions described in the previous table would further stimulate the energy transition in the industrial area of the complex through the partnership with the Port of Rotterdam, enabling it to transform into an international hub for hydrogen production and export to Europe.

Federation of Industries of the State of Ceará

In this challenging moment of energy transition, the Federation of Industries of the State of Ceará (FIEC) is taking action by implementing various programs, projects, and initiatives focused on the hydrogen economy. As a key player in promoting renewable energies, FIEC serves as an important link that would substantiate the H_2V value chain, contributing to Ceará's internationalization in light of current European demand and aligning with the International Energy Agency (IEA) report due to its potential to produce large and more competitive volumes for export to global markets in the long term[44].

These actions demonstrate how FIEC is changing the course of history for the state through investments already made. According to the President of FIEC (2023), in absolute terms, investments made by the FIEC System in the context of energy transition have exceeded R$30 million over the past four years, with three million coming from the German International Cooperation Agency and another twelve million from strategic partnerships with significant international organizations such as Maersk Training.

In prospective studies, the energy sector has received priority attention: "The energy sector is an excellent bearer of future potential." It already plays a significant role in Ceará's economic dynamics, particularly due to its differentiated potential stemming from wind and solar sources. New investments are announced daily across various regions of the state[51].

Identifying opportunities, FIEC has signed several international agreements (MoUs), allowing for direct foreign investments amounting to billions of dollars for H_2V production and future export. Politically, FIEC is aligned with key programs and actions from the Federal Government, such as the National Hydrogen Program (PNH_2), establishing it as an indispensable institutional actor in implementing the hydrogen economy within the context of global energy transition[52].

In this regard, it converges with Brazil's intention to achieve the lowest hydrogen production costs in the world by 2030, consistent with current projections that already position it as one of the most competitive countries regarding production costs[45].

It also aligns with IEA (2021) recommendations for high-level decision-makers in Latin America: a long-term vision for hydrogen within the energy system and international cooperation to position Latin America in the global hydrogen landscape[44].

Part of this leadership can be characterized through various initiatives and activities such as participation in COP26 in Glasgow (Scotland), where it presented on "Green Hydrogen: Investment Opportunities in Northeast Brazil" in 2021; organizing the International Green Hydrogen Forum in 2021; hosting a delegation from the Brazil-Germany Chamber of Commerce and Industry (AHK São Paulo) in 2023; and organizing the event "NRW

HYway2 Brasil: Networking Brazil-Germany: Green Hydrogen" in 2023, bringing together German companies interested in exploring opportunities in Brazil's green hydrogen market[32,53,54].

FIEC has innovated by establishing an environmental sustainability and social responsibility policy that strengthens its systemic governance. In 2022, it launched the ESG-FIEC Program and Center (Environmental, Social, and Corporate Governance), unprecedented throughout Brazil's industrial system. This initiative ("ESG-FIEC Certification Program") incorporated environmental management as an incentive for companies to conduct their activities safely from an environmental standpoint.

As noted by Bezerra (2023), in the industrial sector, manufacturing "green products" without greenhouse gas emissions will constitute a very promising market in coming years due to anticipated taxation on products generating greenhouse gases during their production processes. Furthermore, regarding the ESG Seal FIEC—audited by Bureau Veritas—this program enhances FIEC's competitiveness, credibility, and reliability among global stakeholders, providing greater security during negotiations and attracting investments related to hydrogen economy initiatives[37].

Another initiative was the revival of the Pact for Pecém in 2023, which brings together political, industrial, academic, and civil society sectors with the purpose of fostering multilateral governance alongside socio-environmental sustainability. It is noteworthy that the Pact for Pecém has a significant economic dimension that impacts the socio-economic development of Ceará: the Hydrogen Hub[54].

These actions demonstrate the institution's commitment to hydrogen culture, with the potential to transform the state into a global reference for hydrogen production and export, assuming a leading role at such a crucial time in the first half of the twenty-first century. Finally, FIEC organized a mapping of opportunities expected to arise from the implementation of projects related to H_2V production in the state.

The document, titled Masterplan for Green Hydrogen in Ceará, was conducted by the American consultancy IXL Center and included participation from experts at Harvard University, the Massachusetts Institute of Technology, researchers from various nationalities, a team of senior consultants specialized in innovation, and representatives from various public and private organizations in Ceará[55].

The National Service for Industrial Training (SENAI CE)

The role of SENAI has been fundamental in training specialized human resources to be employed in the energy transition. The institution seeks to strengthen actions, programs, and projects carried out by FIEC. In terms of specialization, it conducts the training programs listed below, having already trained thousands of professionals capable of working in renewable energy.

Table 5: Training Conducted by SENAI

Educational Institution	Course/Training/Qualification	Class Hours
SENAI (Barra do Ceará)	Wind Energy Technology	32 h/class
	Safety Applied to Hydrogen Storage and Distribution	60 h/class
	Wind Turbine Blade Repair	160 h/class
	Photovoltaic System Assembly	40 h/class
	Photovoltaic System Commissioning	40 h/class
SENAI (Barra do Ceará, Juazeiro, and Sobral) H-TEC Project	Hydrogen, Energy Distribution, Wind Energy, Solar Energy, and Occupational Safety	360 h/class
SENAI (Sobral)	Photovoltaic System Assembly	40 h/class

Source: Data from the researchers.

SENAI has taken significant steps in strengthening the value chain of H_2V. In 2022, it joined the Center of Excellence for Energy Transition, in partnership with major multinational companies such as Aeris Energy, Makro, Siemens, Maersk Training, and the German Cooperation Agency (GIZ).

This center aims to enhance workforce training, preparing it to meet the diverse demands of the energy sector in the coming years. The inauguration of the facilities took place in March 2024, contributing to the training of the workforce dedicated to clean energy production in the State. It is equipped with materials and tools imported from the German company Heliocentris, Ali Güleryüz, and Stephan Macher, which will be used for studies related to hydrogen production[57].

Through the partnership with GIZ, three Fuel Cell Automotive Trainer benches, two Fuel Cell Trainer benches, and one Hybrid Energy Lab System were imported, enabling the execution of efficiency, temperature, and pressure tests on a larger scale for applied research on battery and fuel cell systems. In 2023, two significant international missions were carried out in Germany in support of the technological foundations of H_2V.[32]

The first was the International Technical Mission. In the second, SENAI members participated in activities of the bilateral cooperation program "H_2Brasil," an initiative of the Ministry of Mines and Energy (MME) and GIZ. In May 2024, the H-TEC Project for Qualification and Strengthening the Renewable Energy Production Chain in Ceará was launched with the goal of supporting the renewable energy sector by training qualified professionals.

SENAI is responsible for conducting 100% of the practical classes. It is estimated that 1,050 professionals will be trained in the first phase, with an expectation of 10,650 by 2026. Additionally, SESI and SENAI launched a Call for Energy Transition through an innovation grant, offering up to R$ 10 million to foster and develop solutions aimed at industries related to energy transition and ESG topics. This initiative is focused on new products and processes applied to industrial demands. Another goal is to encourage integration between industrial, technological, and educational sectors in developing innovations in the energy transition field.

An international partnership with the Australian multinational Fortescue is also highlighted, aiming to establish a working group to develop initiatives supporting jobs, including workforce training for the H_2V chain. A memorandum of understanding was signed with the Fraunhofer ICT Institute for the development of bilateral research on H_2V and carbon credits.

In 2024, the institution visited the Energy System Catapult at the University of Sheffield and Cranfield in England. The international mission included a visit to the Sustainable Aviation Fuels Innovation Centre (SAF-IC) of the Translational Energy Research Centre (TERC), considered the first in the UK to conduct CO_2 capture processes and hydrogen production, converting it into sustainable aviation fuels.

Euvaldo Lodi Institute (IEL)

The IEL provides business education to the productive sector, with a focus on innovation. Additionally, it plans, executes, and monitors high-complexity projects, contributing to industrial competitiveness at both local and regional levels.

In 2021, IEL became a Scientific and Technological Institution (ICT), establishing itself as a reference in knowledge production and training professionals to work in the energy sector, addressing market demands related to energy transition. As an example, two initiatives were incorporated into the collection of courses offered by IEL: the first was the pioneering MBA class in Renewable Energy Management (392 hours), in partnership with Farias Brito University Center (FB Uni); and the second was the creation of the Renewable Energy and Green Hydrogen Management Training Course (64 hours).

In March 2024, the Renewable Energy Research and Innovation Network of Ceará (Rede VERDES) was launched, a pioneering initiative aimed at conducting basic and applied research in a collaborative and multidisciplinary manner across various types of clean energy. At its launch, Rede VERDES comprised over 100 researchers from 26 Research Units across 14 Higher Education Institutions (IES) and ICTs.

IV. Conclusion

The necessity for energy transition is compelling, as evidenced by studies and reports from renowned institutions. Time has seemingly become short for all the measures that need to be taken to reduce and mitigate the effects of global warming. In this context, renewable energies take on significant importance, in contrast to fossil fuels. Within this framework emerges what is considered the fuel of the future: green hydrogen.

Thus, based on the information presented here, it is concluded that Ceará meets several indicators that make it globally competitive in the energy transition race. Its privileged geographic location in northeastern Brazil, allowing access to key commercial routes to Europe, combined with its natural conditions as a major producer of renewable energy (wind and solar), contribute internationally to Ceará's role as a global player in the green hydrogen value chain, positioning the state as a provider of solutions for energy transition.

Concurrently, the state benefits from the full capabilities and expertise of FIEC, which has been leading numerous actions and initiatives to consolidate the green hydrogen hub in Ceará. It has prioritized promoting the competitiveness and sustainability of the hydrogen economy (ESG), utilizing all available mechanisms to develop a green industry at competitive prices. The study highlighted how Ceará and FIEC are aligned and convergent with key Brazilian policies (MDIC, MCTI, MME, and BNDES) and international studies (IRENA, IEA, IPCC, WEC, McKinsey) on economic decarbonization.

Agreements, partnerships, and foreign investments in Ceará are examples of this awareness. As a disruptive technology, FIEC is convinced of the imperative need to train specialized human resources at all levels, from an MBA in Renewable Energies (IEL) to the technical courses offered by SENAI.

Additionally, priority has been given to adopting innovative practices in implementing the green hydrogen production chain in the state. By monitoring international scenarios, particularly in Europe, with various potential future developments (political, economic, social, technological, and environmental), FIEC has judiciously analyzed these environments and strategically planned the hydrogen economy. The creation of the hydrogen hub at the Pecém port and the partnership with Rotterdam attest to this approach.

This is the context in which Ceará is positioned, full of market opportunities that could turn it into a global benchmark, participating in the global energy transition and altering the state's socioeconomic profile through the production and export of green hydrogen. Therefore, the "Desired Final State" would be for Ceará and FIEC to contribute to the energy transition, benefiting the global environment with the advantages of its natural potential in the production and export of green hydrogen.

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