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THE ROLE OF GREEN HYDROGEN IN THE DECARBONIZATION OF PORTS IN BRAZIL

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ABSTRACT
This article analyzes the role of green hydrogen (H_2V) in the decarbonization of Brazilian ports, focusing on initiatives such as the projects of the ports of Pecém and Suape. It highlights green hydrogen as an alternative fuel produced by electrolysis of water with renewable energy, aligning with the International Maritime Organization (IMO) climate goals. The survey evaluates benefits, such as reducing emissions, generating jobs and strengthening competitiveness, as well as challenges related to production and infrastructure costs. The study also presents global examples, such as the ports of Rotterdam and Yokohama, that integrate sustainable technologies into operations. It concludes that green hydrogen is a viable solution for Brazil's energy transition, with the potential to lead the global clean energy market.

Keywords: Green Hydrogen. Decarbonisation. Brazilian Ports. Sustainability.

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INTRODUCTION

The intensification of the search for clean and renewable energy alternatives in recent decades is directly linked to the growing awareness of the negative impacts of greenhouse gas (GHG) emissions and the urgent need to decarbonize essential sectors of the global economy. The maritime sector, traditionally dependent on fossil fuels, has stood out as one of the main targets of these initiatives, due to its substantial and constant emissions. According to data from the International Maritime Organization (IMO), maritime transport contributes about 2.89% of global carbon dioxide (CO2) emissions, making its decarbonization a strategic priority on the international scene (IMO, 2020).

In response to this need, in 2023, the IMO revised its Greenhouse Gas Strategy, setting ambitious targets, such as a 40% reduction in CO2 emissions by 2030 and 70% by 2050, with the aim of achieving net-zero emissions by the middle of the 21st century. This strategy includes the adoption of alternative fuels, such as green hydrogen (H2V) and other low-carbon ones, and imposes additional pressures on member countries to adapt their policies and regulations to these global goals (IMO, 2023).

Within this context, ports, which are fundamental for global trade and logistics, emerge as focal points for the implementation of sustainable energy solutions. Green hydrogen (H2V), produced from renewable sources through water electrolysis, emerges as a promising alternative for the decarbonization of port operations, contributing to the energy transition in the sector. In Brazil, the strategy of alignment with IMO goals is visible in initiatives such as the National Hydrogen Program (PNH2), which encourages the use of H2V in the maritime sector. Also noteworthy are the ports of Pecém and Suape, which lead pilot projects aimed at the production and use of H_2V, reinforcing the country's commitment to reducing emissions in maritime transport and port activities.

This article aims to discuss the importance of decarbonizing the maritime sector, highlighting the need for clean and renewable energy alternatives in response to concerns about greenhouse gas emissions. It also emphasizes the significant contribution of maritime transport to global CO2 emissions and the urgency of implementing strategies to reduce these emissions, in line with the targets set by the International Maritime Organization (IMO).

Thus, following the introduction, section two provides a brief review of seaports with the main equipment necessary for their operation. Decarbonization is presented in section 4 and in section 5, energy production, as well as its challenges and opportunities, are

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addressed. The understanding of green hydrogen is presented in section 6, so that in section 7 its relationship with the port is discussed. A comparative analysis of cost and environmental impact is presented for a piece of equipment, in order to prove the impact of decarbonization contributing to the reduction of emissions, as well as green hydrogen as a source of clean energy. The study concludes with a brief conclusion about the importance of decarbonization in the search for a more sustainable world.

METHODOLOGY

This study used a qualitative and exploratory approach, focusing on the analysis of initiatives, policies and technologies related to the integration of green hydrogen in Brazilian port operations. The methodology was based on a literature review and document analysis, covering technical reports, academic articles and case studies relevant to the theme.

The data was collected from secondary sources, including reports from the National Waterway Transport Agency (ANTAQ) and the Energy Research Company (EPE), which highlight Brazil's potential for the production and use of green hydrogen in port operations. In addition, academic articles such as those by Carlson and Trencher (2024) and Chen et al. (2024) were used to support the analysis of electrification technologies and alternative fuels in the global port context.

The analysis of initiatives and case studies was carried out to identify decarbonization practices and the use of green hydrogen. The Port of Pecém was one of the main examples in Brazil, being recognized as an emerging green hydrogen hub with electrification and infrastructure projects for the production and export of H_2V. Internationally, the Port of Rotterdam was considered a reference, standing out for its integration of fuel cells and Onshore Power Supply (OPS) systems (EPE, 2022); (PORT OF ROTTERDAM AUTHORITY, 2022).

The environmental, social, and economic benefits of the technologies were evaluated based on indicators reported in the literature, such as the reduction of greenhouse gas (GHG) emissions and the potential for job creation. At the same time, technical and economic challenges, such as high production costs and regulatory barriers, were discussed in the light of experiences reported in other port contexts (CHEN *et al.*, 2024); (HOWARTH *et al.*, 2021).

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To enrich the analysis, a comparison of environmental impact and cost with the cost of an electric truck with a diesel-powered truck was presented. This comparison used metrics such as emissions reduction and operational efficiency, in line with the global decarbonization guidelines established by the International Maritime Organization (IMO) (IMO, 2020).

UNDERSTANDING PORTO

Seaports are complex infrastructures that play a vital role in international trade. They are defined as sheltered areas that allow the berthing of vessels and the movement of cargo and passengers, according to Mamigonian (2017) and CTC Infra (2023).

A seaport is a facility designed to facilitate the loading and unloading of goods and passengers. The main elements that guarantee its functionality according to CTC Infra (1) (2023), Intermodal Digital (2023), National Port System (2023), CTC Infra (2). (2023), PUC-Rio. (2017) include:

- Mooring Area: Space where ships anchor to load or unload goods. This area should be of adequate depth to accommodate different types of vessels.
- Navigation Channels: Water paths that allow for the safe entry and exit of ships. The depth and width of these channels are critical to avoid strandings and ensure the fluidity of maritime traffic.
- Quay or Dock: Structures that allow ships access to land, facilitating the loading and unloading of cargo. The wharves are equipped with cranes and other equipment for cargo handling.
- Storage Areas: Spaces designated to store goods temporarily before or after transportation. These areas can include covered warehouses and outdoor patios.
- Land Infrastructure: Road and rail networks connect ports to the interior of the country, allowing for the efficient flow of cargo. Integration with other modes of transport is vital for modern logistics.

Ports are also home to a variety of industrial facilities and services that support their operations:

- Specific Terminals: Areas within the port dedicated to handling specific types of cargo, such as container terminals, bulk terminals (for bulk products), and liquid terminals (for fuels and chemicals).

- Port Services: These include tugboats, cranes, stevedores, and administrative services that ensure the efficient operation of the port. These services are crucial to optimize the docking time of ships.
- Security and Control Facilities: Integrated systems that ensure the safety of port operations, including environmental monitoring, maritime traffic control, and sanitary inspections.

Ships play a central role in port operations. They range in size and type, from small fishing boats to large freighters. The main types include:

- Cargo Ships: Designed to transport goods on a large scale, they can be specialized in containers, solid or liquid bulk.
- Oil tankers: Specific vessels for the transport of oil and oil products.
- Bulk Carriers: Used to transport agricultural or mineral products in bulk.
- Passenger Ships: These include cruises and *ferries* that transport people between tourist destinations or coastal regions.

EQUIPMENT

Ports use a variety of equipment to ensure efficient cargo handling. This equipment can be classified into two main categories: vertical movement and horizontal movement.

a. Vertical Movement

Cranes: Used to lift cargo from the ship to the dock or vice versa. Gantry cranes are common in container terminals.

Portêineres: Large machines responsible for loading and unloading containers onto ships. They can operate with high efficiency, handling up to 45 containers per hour.

b. Horizontal Movement

Forklifts: Used to move cargo between different areas of the port. There are variations such as electric, gas, and *Reach Stackers*, which are specially designed for container handling.

Conveyor Belts: Equipment used to transport materials between warehouses and cargo areas.

Mechanical Loaders: Specialized equipment for loading bulk solid materials onto ships.

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3.2 ENERGY SOURCES USED

The operation of port equipment requires several sources of energy, which can include:

Fossil Fuels: Many cranes and forklifts still run on diesel or gasoline, although there is growing pressure to reduce the emissions associated with these fuels.

Electric Power: Electric equipment, such as electric forklifts and electric cranes, are increasingly common due to their energy efficiency and lower emissions.

Renewable Energy: Installing solar panels and wind turbines in ports is becoming a common practice to reduce reliance on fossil fuels and minimize the environmental impact of port operations.

The efficiency of port operations depends on the synchronization between ships' activities and land operations. The continuous modernization of port infrastructures is essential to meet the growing demands of global trade, while seeking to minimize environmental impacts to improve logistics operations and promote sustainable practices in the sector. The decarbonization of port activities must be a priority to ensure a more sustainable future in international trade.

DECARBONIZATION

Decarbonization is the process of reducing greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2), to mitigate the impacts of climate change. This concept involves transitioning from fossil fuel-based energy, economic, and industrial systems to low-carbon or zero-carbon alternatives, such as renewables, energy efficiency, and carbon capture and storage (CCS) technologies (UNFCCC, 2015).

Decarbonization is one of the central pillars of the Paris Agreement, which set the goal of limiting global temperature rise to 1.5°C above pre-industrial levels, requiring coordinated efforts by countries to significantly reduce their emissions by mid-century (UNFCCC, 2015).

General decarbonization strategies vary between countries, but have as a common axis the reduction of dependence on fossil fuels and the promotion of renewable energy sources. In the European Union, the European Green Deal seeks to make the continent the first to achieve climate neutrality by 2050. The strategy includes investments in renewable energy, electrification of transport and restructuring of heavy industries, such as steel and cement production, to reduce emissions (EUROPEAN COMMISSION, 2019).

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China, the largest emitter of CO_2 in absolute terms (EUROPEAN COMMISSION, 2024), has committed to peaking its emissions before 2030 and achieving carbon neutrality by 2060. Its strategy includes the massive development of solar and wind energy, as well as investments in carbon capture and storage technologies (CHINA STATE COUNCIL, 2021). Japan and South Korea are also focusing on transitioning to hydrogen as an alternative fuel and increasing the energy efficiency of their industries (IEA, 2021).

In the United States, the second largest global emitter, the *Inflation Reduction Act* of 2022 presents guidelines for large investments in energy and climate security in the country. The law provides significant financial incentives for low-carbon technologies such as electric vehicles, green hydrogen, and solar energy. It is estimated that these measures could reduce US GHG emissions by up to 40% by 2030, compared to 2005 levels (US GOVERNMENT, 2022).

In Brazil, the commitment to decarbonization is strengthened by its predominantly renewable energy matrix. About 84% of electricity in the country is generated by renewable sources, such as hydroelectric, wind, and solar. The National Energy Plan 2050 provides for the expansion of these sources and the integration of green hydrogen technologies, advanced biofuels, and transport electrification systems (MME, 2020).

DECARBONIZATION OF PORTS

In the context of decarbonization, ports play a strategic role in the global context, as they require energy-intensive operations such as cargo handling, berthing operations, port equipment, and logistics activities, emit large amounts of GHG (IMO, 2020).

The energy transition in ports begins with the electrification of essential equipment such as cranes, forklifts, and cargo handling vehicles. This equipment, which traditionally uses fossil fuels, is being replaced by electric or hydrogen-powered versions (CARLSON *et al.*, 2024). Renewable energy sources can be integrated into port operations to power equipment and infrastructure, reducing reliance on electricity generated by fossil fuels.

Sustainable ports are investing in modern technologies and sustainable practices to reduce emissions and increase operational efficiency. Table 1 presents detailed examples of decarbonization initiatives adopted in ports on different continents.

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Table 1: Examples of decarbonization initiatives on different continents

Continent	Harbor	Initiatives	Reference
Asia	Port of Shanghai	Automation, renewable energy	(ALAMOUSH *et al.*, 2023)
Europe	Port of Rotterdam	Electric cranes, LNG and hydrogen infrastructure	(ALAMOUSH *et al.*, 2023)
Americas	Port of Santos	Studies for hydrogen infrastructure	(WEI et al., 2023)
Oceania	Port of Auckland	Investments in renewable energy	(AGARWALA *et al.*, 2021)
Africa	Porto de Durban	Crane modernization and clean energy	(ALAMOUSH *et al.*, 2023)

In addition to the transition to renewable energy, operational efficiency plays an important role. The use of digital technologies, such as *digital twins*, virtual representations that allow simulating the behavior of real systems, real-time monitoring systems and artificial intelligence, allows optimizing the logistics flow and reducing energy waste (EOM *et al.*, 2023). Studies indicate that the application of these technologies can reduce port emissions by up to 50% (CHEN *et al.*, 2024).

The decarbonization of ports is an important part of the attempt to achieve global climate goals and ensure the sustainability of the maritime logistics chain. In addition to reducing greenhouse gas emissions, it promotes economic and social benefits, such as attracting new investments, generating jobs, and strengthening global competitiveness. To maximize this potential, it is essential to implement robust public policies, encourage public-private partnerships, and invest in research and development, transforming ports into sustainable hubs and protagonists in the global energy transition (IMO, 2020).

In shipping, decarbonization is also a strategic measure to mitigate climate change and meet global sustainability goals. The International Maritime Organization (IMO) points out that the sector is responsible for 2.89% of global CO_2 emissions, highlighting the need for coordinated action to reduce its environmental footprint and comply with the Paris Agreement, as well as the targets of its 2023 GHG Emissions Reduction strategy (IMO, 2020).

Among the most recent IMO goals, the goal of net zero emissions by mid-century, with a 40% reduction in carbon intensity by 2030, stands out. Another important point is the expansion of the use of low-emission alternative fuels, such as green hydrogen and ammonia, which should make up at least 10% of the energy consumed by the maritime sector by the same year (IMO, 2023). Despite the great potential for reducing emissions, high production costs and lack of infrastructure are still significant challenges for the

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implementation of these fuels, especially in developing countries (MALLOUPPAS *et al.*, 2021).

Initiatives such as the Poseidon Principles, which promote sustainable financing for low-carbon vessels, are key to accelerating the energy transition (IMO, 2020). In Brazil, the National Hydrogen Program (PNH2) has boosted decarbonization projects in maritime transport. The country, with a robust renewable energy mix that includes hydroelectric, solar, and wind power, has great potential to lead the use of green hydrogen in maritime operations (EPE, 2022).

The transition to more sustainable maritime practices requires global cooperation, technological innovation, and financial support. Alternative fuels, digital technologies, and sound regulatory policies represent the most promising path to achieving climate goals and reducing the sector's carbon footprint. Brazil, with its renewable potential and emerging initiatives, can play a central role in this global transformation.

ENERGY PRODUCTION: CHALLENGES AND OPPORTUNITIES

Energy production is a central issue for sustainable development and climate change mitigation. With the growing need for decarbonization, new energy sources such as green hydrogen are gaining prominence. Energy production in Brazil and in the world, focusing on new energies, especially hydrogen, and discusses the challenges and opportunities associated with these sources.

Brazil is one of the world leaders in renewable energy generation, with an energy matrix that stands out for its sustainability. Approximately 84% of the country's installed capacity comes from renewable sources, the main ones being:

- Hydroelectric plants: They represent about 68% of electricity generation, taking advantage of the country's vast water availability.
- Wind Energy: With accelerated growth, wind energy already accounts for approximately 15% of the electricity matrix.
- Solar Energy: Solar energy has shown a significant increase in installed capacity, contributing about 7% of total generation.

In addition to these traditional sources, Brazil is positioning itself to become a leader in green hydrogen production. Green hydrogen is produced through the electrolysis of water using electricity generated by renewable sources. This process emits no greenhouse gases, making it a promising alternative for decarbonization in hard-to-electrify sectors.

Globally, the energy matrix is still dominated by fossil fuels, which account for about 78% of electricity generation. However, renewables are growing rapidly:

Growth of Renewable Energy In 2022, solar and wind energy were responsible for meeting about 77% of the increase in global electricity demand. The transition to these sources is driven by the urgent need to reduce carbon emissions.

Green hydrogen is emerging as a viable solution for decarbonization in sectors such as transportation, industry, and heating. Produced through electrolysis with renewable electricity, green hydrogen does not generate emissions during its production or use.

Challenges also exist according to Barroso *et al.* (2023), PUCRS. (2023), Ministry of Mines and Energy (2023) and CAF (2024) to be tackled as:

- Cost of Production: The production of green hydrogen is still more expensive than fossil fuel-based alternatives (gray and brown hydrogen). The need for significant investments in technology and infrastructure is a key challenge for its large-scale adoption.
- Storage Technology: The storage and transportation of hydrogen is complex. While hydrogen is an efficient way to store energy, current technologies still need to be improved to ensure safety and efficiency.
- Integration into the Energy Mix: Integrating hydrogen as a significant source within the energy mix requires a reconfiguration of existing infrastructures and public policies that encourage its adoption.
- Legislation and Public Policies: The lack of consistent policies can hinder the advancement of renewable energy.
- Social Acceptance: Local resistance to renewable energy projects can delay their implementation.

Opportunities on the other hand arise in the production of H2Verde according to Barroso et al (2023), PUCRS. (2023), Ministry of Mines and Energy (2023), CIBiogás. (2023), GNPW Group (2023), New Energy. (2023), Ember Climate. (2022) and IEE/USP (2023) as:

- Job Creation: The growth of the renewable energy sector is generating new job opportunities in a variety of areas, from manufacturing to installation and maintenance.

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- Technological Innovation: The sector is fertile for innovations that can improve efficiency in energy generation and storage. Emerging technologies such as artificial intelligence can optimize processes.
- Global Leadership: Countries that lead in the energy transition can set global standards and gain significant economic advantages by positioning themselves as leaders in clean technologies.
- Supporting Sustainability: The transition to renewable energy not only reduces greenhouse gas emissions but also promotes a more sustainable use of natural resources.

It is verified that energy production is undergoing a significant transformation both in Brazil and globally. Green hydrogen emerges as a promising solution for decarbonization, offering substantial economic opportunities while addressing technical and financial challenges. The effective integration of hydrogen into the energy mix can not only help mitigate climate change but also position Brazil as a global leader in renewable energy.

UNDERSTANDING ABOUT H2VERDE

In this section, we will briefly address the green hydrogen production process and its different derivatives.

PRODUCTION PROCESS

Green hydrogen is obtained through water electrolysis, a procedure that uses electricity generated by renewable sources, such as solar, wind, and hydroelectric, to split water into hydrogen and oxygen. This method is considered environmentally sustainable, as it does not release greenhouse gases during its production, unlike gray and blue hydrogen, which are generated from fossil fuels and are associated with significant CO_2 emissions (IRENA, 2020). Projections indicate that the production of green hydrogen could reach 16 million tons per year by 2030, if there are favorable investment conditions and adequate public policies (IEA, 2021).

Green hydrogen presents itself as an alternative to other types, as it uses energy from renewable sources and separates water molecules through the electrolysis process. This production technique does not generate greenhouse gases during its execution, making it a viable option for reducing carbon emissions (SEDAI *et al.*, 2023; SCHMIDT *et al.*, 2020).

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Electrolysis is an electrochemical process that applies electricity to break down chemicals. In the context of green hydrogen production, water electrolysis is used, where water (H2O) is fragmented into hydrogen (H2) and oxygen (O2) by the passage of electric current. The process takes place in an electrolytic cell composed of three main components: two electrodes (anode and cathode) and an electrolyte.

Chemical reactions are represented by the equations:

Anode: $2\ H2O_{(l)} \rightarrow O2(g) + 4\ H+_{(aq)} + 4e^-$

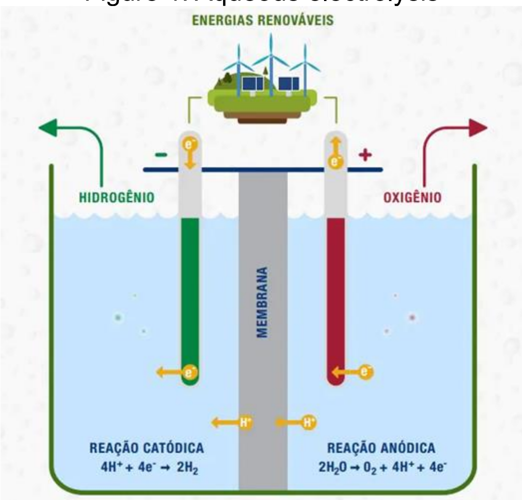
Eq.01

Cathode: $4\ H+_{(aq)} + 4e^- \rightarrow 2\ H2(g)$

Eq.02

The hydrogen produced can be stored and used as an energy source in various applications. Figure 1 illustrates this process.

Figure 1: Aqueous electrolysis



Source: U.S. Department of Energy (2022)

The device used in the process of aqueous electrolysis is the electrolyzer. It plays the role of providing the platform where electrochemical reactions take place to break down water into hydrogen and oxygen. Its function is to optimize the energy efficiency of the process, minimize losses and ensure operational safety.

There are three main types of electrolysis processes currently used according to Albretch *et al*., 2020; Karayel *et al*. 2022; Jansons *et al*. 2023; Lahnaoui *et al*., 2021: (i) alkaline, (ii) polymeric membrane, and (iii) solid oxide electrolysis cells (still in the implementation phase).

Electrolysis units are widely used to generate high purity in hydrogen by breaking

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water, with alkaline electrolysis being one of the oldest techniques for hydrogen production (KARAYEL *et al*., 2022) and the efficiency of existing electrolysis processes varies between 60 and 81% (IEA, 2021).

For the effective production of green hydrogen, it is essential to consider the availability of renewable energy sources, the efficiency of electrolyzers, the infrastructure for storage and transportation, and the costs involved. In Brazil, the abundance of water resources and the growing capacity to generate wind and solar energy put the country in an advantageous position to become a global leader in green hydrogen production (ANEEL, 2021). Water electrolysis requires approximately 50 kWh of electricity to produce 1 kg of hydrogen, making energy efficiency and the cost of electricity critical factors (IRENA, 2020).

DERIVATIVE PRODUCTS

Green hydrogen can be used in various industrial and energy applications. Among the derived products, *Sustainable Aviation Fuel* (SAF), hydrotreated vegetable oil (HVO), ammonia, methanol and green steel stand out.

SAF and HVO

Green hydrogen is crucial in the production of sustainable aviation fuels (SAF) and green diesel, also known as hydrotreated vegetable oil (HVO), both of which are essential for the decarbonization of the transport sector. SAF can reduce CO_2 emissions by up to 80% compared to traditional fossil fuels (ICAO, 2019). HVO, in turn, is a direct replacement for fossil diesel, offering a significant reduction in pollutant emissions (IEA, 2021). SAF is produced from biomass and other waste, while HVO is produced through the hydrogenation of vegetable oils and animal fats, using green hydrogen in the process (IEA, 2021). Global demand for SAF is estimated to reach 100 million tons by 2050, driven by aviation decarbonization goals (ICAO, 2019). The demand for HVO is also expected to grow significantly, with Europe leading the market for advanced biofuels (IEA, 2021).

Ammonia

Widely used in the production of fertilizers, green ammonia, produced from green hydrogen, offers a low-carbon alternative compared to conventional ammonia, which uses natural gas as a feedstock. Global ammonia production is responsible for about 1.8% of

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CO_2 emissions, which can be drastically reduced with the transition to green ammonia (FAO, 2020). In Brazil, the production of green ammonia-based fertilizers can reduce dependence on imports and promote more sustainable agriculture (MME, 2020). In addition to fertilizers, green ammonia can be used as a fuel in marine engines, providing a clean alternative for shipping (IRENA, 2020).

Methanol

Green methanol can be used as a fuel and chemical feedstock, replacing traditional methanol produced from fossil fuels. The production of green methanol can reduce CO_2 emissions by up to 90% (IRENA, 2021). Methanol is an essential input in the production of chemicals such as formaldehyde, acetic acid, and plastics, as well as being used as a fuel in fuel cells and internal combustion engines. Global demand for methanol is expected to grow from 100 million tonnes in 2020 to 500 million tonnes in 2050 as we transition to a low-carbon economy (IRENA, 2021).

Green Steel

Green steel production uses green hydrogen instead of coal, resulting in a significant reduction in CO_2 emissions. European demand for green steel presents a substantial opportunity for Brazil, which is a major exporter of steel. Europe plans to buy only green steel from 2030, which could boost the demand for green hydrogen in Brazil (EUROPEAN COMMISSION, 2020). Green steel is produced through the direct reduction of iron ore using hydrogen instead of coal, resulting in up to a 90% reduction in CO_2 emissions compared to traditional methods (IEA, 2021).

Green hydrogen-derived products have significant advantages in terms of sustainability and reduced carbon emissions compared to their fossil counterparts. For example, SAF and HVO produced from green hydrogen have a significantly lower carbon footprint than traditional fossil fuels (ICAO, 2019). Similarly, green ammonia and methanol offer cleaner and more sustainable production, in line with global decarbonization goals (IRENA, 2020). However, green hydrogen production still faces challenges such as the high cost of production and the need for adequate infrastructure, compared to more established and cheaper traditional methods (IEA, 2021).

The cost of green hydrogen currently ranges between $4 to $6 per kg, while gray hydrogen costs approximately $1 to $2 per kg (IEA, 2021). However, with the reduction in

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the costs of renewable energy and technological advancements, the cost of green hydrogen is expected to fall to around USD 2 per kg by 2030 (IRENA, 2020).

GLOBAL CONTEXT OF GREEN HYDROGEN IN DECARBONIZATION

To deepen the analysis of the role of green hydrogen (H_2V) in the decarbonization of Brazilian ports, it is crucial to contextualize this technology in a global scenario. H_2V has established itself as a central solution in the decarbonization of industrial and mobility sectors in several regions of the world, especially in Europe and Asia.

Countries such as Italy have adopted the creation of hydrogen hubs in their ports as a crucial strategy for the energy transition. These hubs not only provide hydrogen for port operations, but also supply nearby industries, contributing significantly to the reduction of CO_2 emissions. This experience can be an important reference for Brazil, where the implementation of H_2V hubs can transform ports into strategic centers for decarbonization and technological innovation (PIVETTA *et al.,* 2022).

In Asia, China, Japan and South Korea are at the forefront of hydrogen development. China, with the "Hydrogen Industry Development Plan 2021-2035", is investing in both blue and green hydrogen production, as well as expanding its refueling infrastructure, aiming to become one of the largest producers and consumers of hydrogen by 2035 (CHINA HYDROGEN ALLIANCE, 2021).

Japan, with its 2017 "*Basic Hydrogen Strategy*", aims to become a hydrogen-based society by 2050, with a focus on importing H_2V from regions with high renewable energy availability, such as Australia. South Korea, through the "*Hydrogen Economy Roadmap*", launched in 2020, has set goals to be among the five largest hydrogen economies by 2040. Both countries are investing heavily in infrastructure and public policies for hydrogen development, with an emphasis on the port and mobility sector (SASAKI *et al*., 2020; CHUNG *et al*., 2021).

In addition to China, Japan and South Korea, India also stands out as a potential leader in the hydrogen economy, with its *2021 "National Hydrogen Mission*", seeks to consolidate itself as one of the largest producers and exporters of H_2V, taking advantage of its abundant solar and wind resources to reduce dependence on fossil fuels and achieve its decarbonization goals by 2050 (GOVERNMENT OF INDIA, 2021).

These global examples demonstrate that robust public policies, combined with substantial investments in infrastructure, are critical to the successful implementation of

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H_2V. Brazil, with its vast potential in renewable energies such as solar and wind, has the opportunity to follow these examples and apply similar strategies. The creation of H_2V hubs in Brazilian ports would not only contribute to the decarbonization of port operations, but also attract international investments, consolidating the country as a global leader in the energy transition.

ENVIRONMENTAL IMPACTS ON H2V PRODUCTION

Although green hydrogen stands out as a clean energy source in terms of greenhouse gas (GHG) emissions, its production is not without environmental impacts. One of the main challenges is related to the intensive use of water resources, since the electrolysis process requires large volumes of water. This factor can represent a considerable obstacle, especially in regions with water scarcity. In addition, the production of H_2V can generate by-products that need proper management to prevent environmental contamination. In order for the environmental benefits of green hydrogen to be maximized and its negative impacts minimized, it is essential that sustainable practices and strict environmental regulations are adopted (ULLMAN *et al.*, 2022).

Compared to other forms of hydrogen, such as gray and blue hydrogen, green hydrogen has a significant advantage due to its very low GHG emissions. Gray hydrogen, produced from fossil fuels, emits between 9 and 12 kg of CO_2 per kg of hydrogen generated, which directly contributes to the increase in global emissions (EPE, 2022). Blue hydrogen, which uses carbon capture and storage (CCS) technologies, can reduce these emissions to approximately 2 to 3 kg of CO_2 per kg of hydrogen, depending on the efficiency of the capture process. However, blue hydrogen faces significant obstacles, such as the variable efficiency of CCS and the risks of CO_2 leakage during storage, which can compromise the environmental gains of this technology (HOWARTH *et al.*, 2021).

On the other hand, green hydrogen is produced from renewable sources, such as solar and wind energy, through the electrolysis of water, which results in virtually zero CO_2 emissions. However, high water consumption remains a significant environmental concern: it is estimated that around 9 liters of water are needed to produce 1 kg of hydrogen by electrolysis (SENAI, 2023). To mitigate this impact, Brazil has invested in the development of desalination technologies and in the reuse of reused water, especially in regions such as the Northeast, which has an abundance of renewable resources and proximity to coastal areas, which favors the implementation of these solutions (BRASIL, 2021).

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Green hydrogen is consolidating itself as the most sustainable alternative in the long term, especially in the Brazilian context, where there is a vast potential for renewable energies. The National Hydrogen Plan (PNH_2), launched by the Brazilian government, aims to foster the development of H_2V, taking advantage of the abundant solar and wind resources, especially in the Northeast region. In this region, the environmental impact of green hydrogen production can be significantly mitigated through the implementation of advanced technologies, such as desalination and water reuse (BRASIL, 2021; EPE, 2022). In this way, green hydrogen not only contributes to meeting climate goals, but also presents itself as a viable and sustainable solution for Brazil's energy future.

LOW-CARBON POWER GENERATION

Another promising application of green hydrogen (H_2V) in Brazilian ports is the generation of energy through fuel cells. Currently, many ports rely on the conventional electricity grid to sustain their operations, which can present problems in terms of both cost and energy security, especially in regions where power supply is limited or unstable. Electricity generation using hydrogen fuel cells can provide a local, clean and reliable source of energy that can power port operations continuously and with less environmental impact.

The implementation of power generation systems from H_2V offers the opportunity to reduce the dependence of ports on the traditional electricity grid, providing greater energy resilience. This aspect becomes particularly relevant in a context of growing demand for electricity and possible restrictions on energy supply due to extreme weather events or failures in electrical infrastructure. In addition, the use of H_2V as an energy source contributes to the reduction of greenhouse gas (GHG) emissions associated with electricity generation, especially in regions whose energy matrix still relies heavily on fossil sources (Serratt et al., 2024).

International experiences demonstrate the successful use of hydrogen fuel cells in port operations. At the Port of Yokohama in Japan, a pilot project implemented the use of fuel cells to power cranes and provide electricity to part of the port facilities. Developed in partnership with Japanese technology companies, the project aims to reduce CO_2 emissions and increase the port's energy efficiency. This initiative is part of Japan's strategy to become a hydrogen-based society by 2050, applying this technology in critical sectors such as transport and port logistics (METI, 2021).

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Another important example is the Port of Rotterdam in the Netherlands, which is investing in the integration of hydrogen fuel cells into its operations. The port has been using hydrogen to power mobile generators and forklifts, reducing its reliance on diesel generators. The use of fuel cells at the Port of Rotterdam is part of a broader plan to transform it into a green hydrogen hub in Europe, with significant investments in infrastructure aimed at the production, storage and distribution of H_2V. The goal is to create a sustainable port model that can be replicated in other regions of the world (PORT OF ROTTERDAM AUTHORITY, 2022).

In Brazil, local researchers and projects are also advancing in the application of this technology. Studies carried out within the scope of the SENAI Institute for Innovation in Renewable Energies highlight the potential of hydrogen fuel cells for use in ports, especially in the Northeast, where there is an abundance of renewable energy sources, such as solar and wind. Brazilian researchers have been analyzing the feasibility of implementing fuel cell systems at the Port of Pecém, which is already positioned as one of the main green hydrogen hubs in the country (SENAI, 2023). These projects seek to integrate the production of hydrogen with its direct use in port operations, promoting the reduction of emissions and energy independence.

These examples, both international and national, highlight the great potential of hydrogen fuel cells to transform port operations into true sustainable energy hubs. In Brazil, the integration of fuel cells in the port sector, as is already being studied at the Port of Pecém, would not only reduce GHG emissions, but also increase the energy resilience and global competitiveness of Brazilian ports.

In addition to the Port of Pecém, other Brazilian ports are starting initiatives aimed at decarbonization. The Port of Suape, in Pernambuco, has an ongoing project for the installation of a pilot plant for the production of green hydrogen, using solar and wind energy. Similarly, the Port of Santos, the largest in Latin America, is also exploring the implementation of H_2V technologies to reduce its emissions and position itself as a clean energy hub. Table 2 exemplifies some ongoing initiatives for the production and development of H2V in Brazil

Table 2 Ongoing initiatives for H2V production in Brazil

Harbor	Location	Ongoing initiatives	Partners
Port of Pecém	Ceará	Green Hydrogen Hub; H2V production, storage and export	Port of Rotterdam, Government of Ceará, private companies
Port of Suape	Pernambuco	Feasibility studies for the production and use of H2V; Development of pilot projects	Government of Pernambuco, private companies
Port of Açu	Rio de Janeiro	H2V production from offshore wind energy; Truck and ship supply	Government of Rio de Janeiro, private companies
Other ports	Diverse regions	Feasibility studies; Development of pilot projects	State governments, private companies

Note: The table presents some of the main green hydrogen initiatives in Brazilian ports. It is important to note that new projects and partnerships are constantly developing, driving the expansion of the H2V market in Brazil.

GREEN HYDROGEN AND THE BRAZILIAN PORT SECTOR

Brazil has a vast port network, consisting of 37 public ports and more than 120 terminals for private use, according to data from the National Waterway Transportation Agency (ANTAQ). These ports play a crucial role in the country's economy, being responsible for a large part of national exports and imports. In this context, the adoption of technologies aimed at decarbonization, such as green hydrogen (H_2V), becomes an essential measure to reduce greenhouse gas (GHG) emissions associated with port operations and maritime transport.

The introduction of H_2V in Brazilian ports is a key strategy for the decarbonization of port activities, configuring itself as a decisive step in Brazil's energy transition. This process involves the gradual replacement of fossil fuels with green hydrogen in various operations, which not only generates significant environmental benefits, but also drives technological innovation and promotes a significant increase in operational efficiency.

PORT EQUIPMENT

Port equipment, such as forklifts, cranes, tugboats, and other vehicles used in daily operations, are largely responsible for the emission of local pollutants, such as nitrogen oxides (NOx) and fine particulate matter (PM). The adaptation or replacement of this equipment with models powered by hydrogen fuel cells offers a significant opportunity for the reduction of emissions, in addition to contributing to the reduction of the noise level in port areas. Studies indicate that electrification of port equipment through the use of hydrogen fuel cells can reduce NOx emissions by up to 80% and virtually eliminate fine particulate matter, positively impacting air quality and public health in communities around ports (CHEN *et al.,* 2024).

The use of H_2V in port equipment also provides important operational advantages, such as longer range and significantly shorter recharge times compared to conventional electric batteries. For example, a hydrogen-powered forklift can be refueled within minutes, while a battery-electric forklift can take several hours to complete its charge. This results in greater operational efficiency, with reduced equipment downtimes and an increase in the overall productivity of port operations (CARLSON *et al.*, 2024).

Several pilot projects around the world are already exploring the use of hydrogen-powered equipment in ports. A prominent example is the Port of Los Angeles, in the United States, which is conducting tests with trucks powered by hydrogen fuel cells. This project is part of a broader port transport decarbonization initiative, with the ambitious goal of reducing carbon emissions by 100% by 2035. The Port of Los Angeles collaborates with companies such as Toyota and Kenworth to develop and test these H_2-powered trucks, which are already being used in daily operations of transporting goods in and out of the port (CALIFORNIA AIR RESOURCES BOARD, 2022).

In Brazil, the Port of Pecém, in Ceará, is also standing out as a center for innovation in green hydrogen, focusing not only on the export of H_2V, but also on the use of hydrogen-powered port equipment. The project includes the use of cranes and other heavy-duty vehicles powered by fuel cells, making it one of the first ports in Latin America to adopt this technology. This pilot project is being developed in collaboration with private companies and research institutions, in line with the objectives of the National Hydrogen Program (PNH_2) (EPE, 2022).

These examples illustrate that the use of green hydrogen in port equipment is already an expanding reality, with great potential to be expanded globally. The implementation of H_2V in ports such as Los Angeles and Pecém not only demonstrates the feasibility of this sustainable solution, but also highlights its potential to significantly increase operational efficiency.

Another important initiative, fundamental for the decarbonization of the operation of ships within ports, is the application of the OPS (*Onshore Power Supply*) System, also known as "*cold ironing*" or "*shore-to-ship power*", a technology that allows docked ships to turn off their diesel-powered auxiliary engines and connect to a local power grid and use the electricity. which significantly reduces CO_2, NOx and SOx emissions.

The OPS has currently been the best option for decarbonizing the operation of docked ships, also contributing to a reduction in noise levels. Its implementation in

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Brazilian ports is close to a reality, given that some strategic ports already consider this technology as initiatives that make up their ESG Agendas.

In Europe, the ports of Germany, Sweden and Norway are at the forefront of applying this solution to serve large commercial and cruise ships. Table 3 presents some benefits and environmental impacts related to the decarbonization of port equipment.

Table 3. Environmental impacts and benefits related to the decarbonization of port equipment

Benefit	Environmental impact
1. Reducing carbon emissions	Eliminating the use of diesel engines significantly reduces greenhouse gas emissions and pollutants.
2. Improvement in air quality	With the reduction of air pollutants, the air quality in port regions is considerably improved, benefiting public health.
3. Compliance with environmental regulations:	European countries have adopted strict regulations that encourage or mandate the use of OPS, contributing to sustainability objectives.
4. Noise reduction:	The shutdown of auxiliary engines also reduces noise levels, positively impacting the urban environment near ports.

Table 4 presents examples of ports around the world that have already implemented the Onshore Power Supply (OPS) system and other technologies aimed at decarbonization:

Table 4 - Some ports that already use the OPS

Harbor	Location	Technology implemented	Year of implementation	Environmental impact
Porto de Los Angeles	USA	Onshore Power Supply	2013	30% reduction in NOx emissions during operations.
Port of Rotterdam	Netherlands	Onshore Power Supply	2015	Significant decrease in CO_2 emissions during berths.
Port of Hamburg	Germany	Bunkering with LNG and OPS	2018	50% reduction in GHG emissions in port operations.
Port of Singapore	Singapore	Onshore Power Supply	2020	Improved air quality and reduced local emissions.
Port of Shanghai	China	Infrastructure for hydrogen	2022	Beginning of the transition to alternative fuels.
Port of Pecém	Brazil	Onshore Power Supply	2024 (expected)	Potential to significantly reduce local emissions.

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These examples demonstrate how the implementation of technologies such as *Onshore Power Supply* and other innovations can contribute to the decarbonization of seaports, promoting a more sustainable environment and reducing emissions associated with port operations.

Figure 1 presents some of the most important equipment used in the operation of ports where the most used fuels are diesel and we also present the possible low-carbon energy routes, where electricity and hydrogen appear.

Figure 1 - Port Equipment with their respective fuels used and possible routes to be used

Source: by the author himself.

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Figures 2 and 3 show the equipment currently used in the vast majority of ports with their respective alternative route for decarbonized energy and some of the equipment already on the market, from fossil to decarbonized energies.

Figure 3 – Equipment available on the market

Fonte: US Department of Energy

EXAMPLE OF ENVIRONMENTAL IMPACT

A study by XCMG do Brasil as shown in Figure 4 presents a cost comparison of an electric truck with a diesel truck (VW Constellation 30.320 8x2 diesel-E6) and the E7-29R XCMG electric truck.

Initiatives to decarbonize cargo transport and cargo handling equipment have prospered significantly in the world. Currently in Brazil, there are already companies that promote the decarbonization of these transport and cargo handling equipment through the development of *powertrain*[4] solutions compatible with the reality of each territory.

As an example of one of these *powertrain* solutions on the market and accessible to logistics, transport and port operation companies, *XUZHOU CONSTRUCTION MACHINERY GROUP – XCMG*, A Chinese multinational, invested 0.5 billion dollars in the implementation of an equipment factory in Pouso Alegre - MG with a production capacity of 10,000 pieces of equipment per year, with configurations of thermal engines (Biofuels),

[4] From the moment you start and the spark plug starts the engine until the force generated by it is transferred to the drive wheels, it goes through a system. The set: clutch, gearbox, drive shafts, differential and drive wheels is called Powertrain or powertrain.

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hybrids (thermal and electric), electric (BEV) and engines powered by electricity generated from hydrogen cells.

Global initiatives such as the one promoted by XCMG are responsible for putting the decarbonization of logistics and transport operations on a higher scale level, considering that the predominance of cargo that is transported from the point of origin to the ports, and which are later moved internally in the port yards and terminals, use equipment with engines predominantly powered by diesel combustion.

The table below compares the costs of the two cargo vehicle solutions, the XCMG E7-29R Electric Truck and the VW 28,480 Meteor (E6 Diesel):

Figure 4 – Comparison of the cost carried out by XCM-Brazil Company of a diesel and electric truck

E7-29R Caminhão Elétrico XCMG

Comparativo de Custo: Caminhão Diesel (VW Constellation 30.320 8x2 (diesel - E6) x Caminhão			
Km diaria	150		
Dias por semana	6		
Km Mês	3.600		
Km ano	43.200		
Km para Amortizar o Investimento	**187.172**		
Tempo para Amortizar o Investimento	**4,33**		
	VW Constellation 30.320 8x2	**Custo Energia fora de Pico ou Mercado Livre E7-29R**	**Economia**
Valor de Aquisição FIPE	**741.500**	**1.000.000**	**-258.500**
Consumo Médio Km/L - Km/Kwh	3,00	0,67	
Preço/Litro Diesel - Kwh	5,71	0,43	
Custo de Abastecimento	**356.251**	**122.083**	234.168
Custo Abastecimento /Km rodado	1,90	0,65	**1,25**
Consumo Arla (Km/l)	50	-	
Preço/Litro Arla	4,00	-	
Custo de Arla	**14.974**	-	**14.974**
	0,08		
Custo Abastecimento + Arla	**371.225**	**122.083**	**249.141**
Valor Acumulado de Manutenção	**56.152**	**46.793**	**9.359**
Manutenção/Km rodado	0,30	0,25	**0,05**
Custo Operacional Total	**427.377**	**168.877**	**258.500**
Custo Operacional / Km Rodado	**2,28**	**0,90**	**1,38**

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Figure 5- Results presented by XCMG company of the environmental impact

XCMG

- Redução de **65**% de custo por km rodado de R$ 1,90 para R$ 0,65 por Km no elétrico.
- Em 4 ano teremos uma redução de CO2 para a atmosfera em torno **47.000**t/ ano, por cada caminhão.
- Evitando consumo de mais de **15** mil litros de óleo Diesel por Caminhão.
- Credito de Carbono
  Valor do Carbono = 1.000 toneladas x $76,46/tonelada.
  47.000T x $76,46= $3.593.62

The transition to electric vehicles in the transportation sector, especially trucks, is an important strategy to reduce greenhouse gas emissions and promote sustainability. This study analyzes the economic and environmental impact of adopting electric trucks compared to diesel trucks, considering several factors such as acquisition cost, consumption, energy price, supply cost, Arla cost, maintenance per kilometer driven and total operating cost.

COST ANALYSIS

The initial investment in acquiring an electric truck is usually higher than that of a diesel truck. However, the difference of R$258,500.00, which is amortized in 4 years and then presents a positive result during its useful life, justifying this choice. This value considers not only the purchase price, but also the savings generated in consumption and maintenance.

Electric trucks have significantly higher energy efficiency. While a diesel truck consumes about 15 thousand liters of fuel per year, an electric truck uses electricity which, in financial terms, results in a reduced operating cost. With the average price of electricity being lower than that of diesel, the savings become evident. The cost per kilometer driven for the electric truck is reduced by up to 65% compared to the diesel truck.

Diesel trucks require the use of Arla (Liquid NOx Reducing Agent), which represents a significant additional cost. In contrast, electric trucks do not have this need, eliminating costs associated with purchasing and storing this additive.

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Maintenance costs for electric vehicles are considerably lower due to the lower number of moving parts and the absence of components such as oil filters and exhaust systems. This results in a significant reduction in total operating costs.

ENVIRONMENTAL ANALYSIS

The adoption of electric trucks not only generates substantial financial savings, but also contributes significantly to the reduction of carbon emissions. This study estimates that the transition to electric trucks can avoid the emission of approximately 47 thousand tons of CO_2 per year over four years. This reduction is achieved by eliminating the consumption of more than 15 thousand liters of diesel that would be used by a conventional truck. In addition, this change generates an estimated carbon credit of US$3,593.62 annually, contributing to the financial sustainability of logistics operations and promoting more responsible business practices.

The comparison between diesel and electric trucks reveals that the transition to electric vehicles not only offers significant economic advantages through reduced total operating costs, but also plays a crucial role in mitigating climate change. With an estimated saving of R$258,500.00 that is amortized in 4 years and then presents a positive result during its useful life, justifying this choice, in addition to a substantial reduction in CO_2 emissions, electric trucks are positioned as a viable and sustainable solution for the future of transportation.

CONCLUSION

The advancement of green hydrogen in Brazil represents an opportunity to complement the country's energy matrix, strategically aligning with global sustainability and decarbonization goals. The integration of green hydrogen in Brazilian port operations, as in the emblematic case of the Port of Pecém, reinforces the national commitment to reducing greenhouse gas emissions and consolidates Brazil as an emerging player in the global hydrogen economy.

For Brazil to stand out in this scenario, it is essential to expand the infrastructure for the production, storage, and distribution of green hydrogen. This evolution will require significant investments in technology and innovation, as well as strategic partnerships, such as collaboration with national and international actors, which can accelerate the development of green hydrogen hubs with international relevance.

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Strengthening the regulatory framework will be a crucial pillar to ensure the competitiveness of Brazilian green hydrogen in the global market. Public policies that encourage its adoption, associated with certification mechanisms and sustainability standards, are essential to ensure that hydrogen produced in Brazil is recognized as reliable and sustainable in international markets.

The transition to green hydrogen will bring profound socio-economic impacts, including job creation, local economic development, and improved quality of life for communities near ports. However, for this transition to be equitable, it is essential to offer support and training to workers currently dependent on fossil fuel industries, ensuring their integration into the new opportunities of the hydrogen economy.

In the long term, the integration of green hydrogen in Brazilian ports can serve as a model to decarbonize other critical sectors, such as industry and transport. The success of this energy transition will be crucial for Brazil's sustainable development and to strengthen its position as a leader in the global renewable energy arena.

In the coming years, it will be of paramount importance for Brazil to capitalize on its vast natural resources and technological advancements to establish itself as a global power in the hydrogen economy. Overcoming regulatory, technological, and socioeconomic challenges will be decisive in ensuring that green hydrogen plays a central role in the country's energy transformation and in promoting a more sustainable future.

With a clear strategic vision and a solid commitment to innovation and sustainability, Brazil has a unique opportunity to lead the transition to a low-carbon economy, positioning hydrogen as an essential pillar of a greener, more resilient, and prosperous future.

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