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Bibliographic Analysis Of The Main Challenges And Opportunities Of Green Hydrogen Production (H_2V) In Brazil And Worldwide

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Abstract:
Background: *In the global context of the energy transition, the production of green hydrogen (H_2V) has emerged as a promising alternative. H_2V, produced through water electrolysis powered by renewable energy sources, is a key means of reducing greenhouse gas emissions and advancing towards a more sustainable energy matrix.*
Materials and Methods: *This research adopted a qualitative approach with the aim of understanding the main challenges and opportunities in H_2V production both in Brazil and globally. The research method involved a bibliographic review, examining 17 sources of scientific knowledge.*
Results: *The overall objective of this study is to analyze the key challenges and opportunities associated with H2V production in Brazil and on a global scale, based on a comprehensive bibliographic review of the scientific and technical literature on the topic. The study identifies trends, technological, economic, and regulatory barriers, as well as the potential for implementing this sustainable energy source.*
Conclusion: *This study aims to demonstrate that H_2V can become a relevant solution to support the achievement of global climate targets and the socioeconomic development of nations with a more renewable energy matrix. By identifying opportunities and challenges, this study establishes a foundation for future investigations into incentive policies, technological improvements, and the integration of this energy into the global matrix.*
Keywords: *Energy Transition; Green Hydrogen; Renewable Energy; Sustainable Energy Matrix.*

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I. Introduction

According to Turner (2004), since the 1930s, the possibility of a hydrogen-based economy (H_2) has been envisioned, enabling the efficient storage of this form of energy[1]. This approach offers significant advantages, such as reducing environmental emissions and ensuring an alternative fuel source for the transportation sector. However, the author emphasizes that achieving this milestone requires concentrated and coordinated efforts. In this context, the world is intensely seeking solutions to promote the decarbonization of the economy, aiming to significantly reduce greenhouse gas (GHG) emissions. These gases are the primary drivers of large-scale catastrophes and the climate transformations observed in recent years. Within this scenario, the global community joined forces to establish the Paris Agreement in 2015, setting clear targets to limit the temperature increase to 1.5ºC by the end of the century[2].

According to Climate Watch (2020), a portion of these GHG emissions consists of carbon dioxide (CO_2), which is predominantly released by economic activities involving the combustion of fossil fuels (FF). These activities span various sectors, such as transportation (due to the burning of diesel and gasoline), industrial processes, and energy production, with a significant share emitted by thermoelectric plants[2].

Bezerra (2021) suggests that an effective way to fulfill the commitments stipulated in the Paris Agreement involves reducing greenhouse gas emissions into the atmosphere, particularly CO_2, by substituting fossil fuels with renewable energy sources. In this regard, Bezerra (2021) asserts that transitioning to a low-carbon economy can be achieved by incorporating hydrogen (H_2) into industrial processes, positioning it as a viable energy alternative to fossil fuels[3].

The primary objective of this research is to analyze the main challenges and opportunities associated with H_2V production in Brazil and globally, based on a comprehensive literature review of scientific and technical studies on the subject. The study aims to identify trends, technological, economic, and regulatory barriers, as well as the potential for implementing this sustainable energy source.

The specific objectives are as follows: - To explore the role of H_2 as an essential energy source within the context of energy transitions, highlighting its properties, applications, and potential to replace fossil energy sources. - To analyze the specific characteristics of H_2V, distinguishing it from other forms of H_2 and emphasizing the generation processes that make it a sustainable, low-carbon alternative. - To investigate the impact of H_2V on the global economy, addressing its potential to generate jobs, establish new industrial complexes, and attract investments in renewable energy infrastructure and technology. - To assess the specific opportunities and challenges for the development and implementation of H_2V in Brazil, considering the country's energy and environmental context, as well as public policies and initiatives supporting this technology.

This article is organized into four sections. The first section provides an introduction, presenting the objectives of this research. The second section outlines the methodological procedures employed in this study. The third section develops a theoretical foundation comprising a bibliographic discussion among various authors addressing the same theme. Finally, the fourth section presents the concluding remarks, indicating potential directions for future research.

II. Material And Methods

This research adopted a qualitative approach to understand the main obstacles and opportunities associated with the production of H_2V both in Brazil and globally. The choice of a qualitative approach is justified by its exploratory and interpretative nature, aimed at deepening the understanding of a complex phenomenon within the context of renewable energy (RE) and energy transitions.

Scientifically, qualitative research is crucial as it enables a detailed assessment of the elements involved, providing insights to support future policies and strategies in critical fields such as energy sustainability. The research method involved a bibliographic review, analyzing 17 scientific sources. The selection of articles aimed to ensure the quality and relevance of the information, with most publications classified as QUALIS A1, ensuring the reliability and depth of the analysis.

The following authors made the most significant contributions to this research: Fernandes et al. (2023), Lara and Richter (2023), and Souza (2024). Their contributions were instrumental in consolidating the understanding of the challenges and opportunities in the application of green hydrogen, providing a robust foundation for the study's conclusions and recommendations.

III. Literature Review

The globalized world, climate change, and intense political tensions among nations make it highly risky not to have a diversified energy matrix. If a key supplier within a country's energy matrix declines, the nation may often face an urgent energy crisis. Fernandes et al. (2023) explain that countries are developing plans to reduce their dependence on fossil fuels (FF) and are investing in renewable energy initiatives[4; 5].

Whether seeking tax incentives or environmental quality certifications, the pursuit of less polluting energy methods is often a strategic objective for companies aiming to enhance their competitiveness. Bezerra (2021) highlights that environmental concerns are among the primary topics discussed on the global stage, with one of the most significant events being the Paris Agreement in 2015. The issue of global warming gains substantial attention during environmental catastrophes[3].

According to Bezerra (2021), having an environmental policy increases a nation's relevance in global discussions[3]. The existence of fiscal incentive policies or easier access to financing contributes to the rising adoption of clean energy (CE) methods, taking advantage of the growing green movement. In the global context of energy transition, the production of green hydrogen (H_2V) has emerged as a promising option. H_2V, produced through water electrolysis using renewable energy sources, serves as a decisive tool for reducing greenhouse gas emissions and advancing toward a more sustainable energy matrix.

The challenges faced are diverse in complexity and scope, encompassing technological, economic, political, and environmental issues. To ensure that future research, public policies, and investments are directed appropriately, a deep understanding of these challenges is essential. Furthermore, the goal is to identify opportunities where cooperation and innovation can promote the sustainable development of H_2V production by analyzing emerging prospects in this field.

Hydrogen as an Essential Energy Source

Hydrogen gas is one of the byproducts obtained through the electrolysis of water molecules. As an emerging alternative, Fernandes et al. (2023) indicate that a kilogram of hydrogen (H_2) can generate more than twice the energy of natural gas (NG) while emitting no greenhouse gases. Companies that adopt this clean energy source can enhance their public image, aligning with the growing support for environmental policies[4]. Although hydrogen is the most abundant chemical element on Earth, comprising approximately 93% of the planet's matter, it is rarely found in its pure form.

Forte and Gazillo (2023) emphasize that, due to its potential for using only non-polluting elements, such as water and oxygen, during its production and use, hydrogen possesses high value-added characteristics, aligning with the environmental policies frequently emphasized in global environmental summits[6].

Hydrogen gas, as noted by Forte and Gazillo (2023), can also be used for petroleum refining, steel production, fertilizers, food processing, and the transportation sector. Additionally, it can be stored in tanks as a gas or liquid, facilitating the transfer of its potential energy to remote areas without access to conventional energy transmission or distribution systems. In such areas, its potential energy can power electric generators or engines for various functions[6].

Lara and Richter (2023) suggest that long-distance maritime and air transportation are key targets for promoting hydrogen as a fuel. In these contexts, hydrogen can serve as both a motor fuel and a source of electricity for crew operations[7].

Fernandes et al. (2023) report that in 2020, 90 million tons of hydrogen were produced, with expectations that this figure will more than double by 2040. Due to its role as a clean energy alternative, banks and international financing groups often provide favorable terms to companies with robust green policies, including hydrogen producers. This financial encouragement is also one reason why foreign investments target Brazil for renewable energy (RE) projects[4].

According to Lara and Richter (2023), hydrogen's high energy density offers a strategic advantage for countries with RE-integrated energy matrices, such as Brazil. Within Brazilian territory, the potential exists for a diversified green energy matrix. The origin of the electricity required for H_2 production is critical in determining whether the hydrogen qualifies as green[5;7].

Although producing hydrogen gas and compressing it into liquid form requires significant energy expenditure, manufacturing costs can be offset through credits and incentives for clean energy (CE) usage. Table 1 demonstrates that water can achieve up to 96% of the maximum efficiency of natural gas or coal as a hydrogen source.

Table 1 – Methods of Hydrogen Gas Production

Raw Material	Production Method	Energy Efficiency	Source
Water	Electrolysis	61–82%	Parra et al. (2019)
Biomass	Thermolysis via Pyrolysis	35–50%	Dawood, Anda, and Shafiollah (2020)
Biomass	Thermolysis via Gasification	35–50%	El-Emam and Özcan (2020)
Coal	Thermolysis via Gasification	74–85%	Mah et al. (2019)
Hydrocarbons	Partial Oxidation of Fossil Fuels	60–75%	Pinsky et al. (2020)
Natural Gas	Methane Steam Reforming	74–85%	Pinsky et al. (2020)

Source: Lara and Richter (2023)[7; 13; 14; 15; 16; 17]

Bezerra (2021) adds that the main producers of H2 as an energy source are the United States, Russia, China, France, and Germany. Furthermore, within the context of H2 as an energy source, Japan aspires to become the leading economy in H2. This highlights how the race for H2 demand could represent a strategic global differentiator in the coming years[3].

The Specificity of Green Hydrogen

Although H_2 is a colorless gas, it is classified by a specific color based on its extraction method, as shown in Table 2. H_2 is designated as green when it is produced using renewable energy sources (RES), such as wind or solar power, to generate the electricity required for its production via electrolysis. According to Lara and Richter (2023), green hydrogen (H_2V) is a fully greenhouse gas (GHG) emission-free option, both in its use and throughout its production chain[7].

Table 2 - Hydrogen Classification by Colors

Type	Characteristic
Brown Hydrogen	Brown hydrogen is obtained through the gasification of coal, without carbon capture. It is considered harmful to the environment.
Gray Hydrogen	Gray hydrogen is produced through steam reforming of natural gas (NG) and also lacks carbon capture, making it harmful to the environment.
Blue Hydrogen	Blue hydrogen is obtained through steam reforming of fossil fuels (FF) with carbon capture and reuse, making it more efficient compared to gray and brown.
White Hydrogen	Produced through the extraction of natural, or geological, hydrogen.
Turquoise Hydrogen	Produced through methane pyrolysis and does not generate carbon emissions.
Green Hydrogen	Green hydrogen (H2V) is produced through water electrolysis, using electricity from renewable energy sources.
Moss Hydrogen	Produced from biomass, with or without Carbon Capture, Utilization, and Storage (CCUS), through catalytic reforming, gasification, or anaerobic biodigestion.
Pink Hydrogen	Produced through water electrolysis, using electricity supplied by nuclear energy.

Source: Forte and Gazillo (2023) [6]

Lara and Richter (2023) add that green hydrogen (H_2V) can also be compressed, possessing a high energy density when in its liquid form, making it an excellent energy source for land or maritime transportation. According to Lara and Richter (2023), liquid hydrogen occupies 700 times less space in its liquid state, facilitating storage and transportation in fuel tanks. With climate issues increasingly at the forefront of major national and international discussions, H_2V represents an excellent investment for the industrial sector[7].

Currently, according to Gonçalves (2023), only 1% of the world's hydrogen production is green. Although this may seem small, this share generated approximately $300 million in 2020. The continuous growth in demand and consumption of H_2V significantly impacts both the hydrogen market itself and the transportation and energy sectors. Although it is a green energy source, hydrogen gas remains a flammable fuel that must be transported to the site of its use. This requires a robust and secure infrastructure to minimize the risk of accidents[8].

Viegas (2021) notes that there is also a technological race to improve hydrogen gas production efficiency, enhance its energy utilization, and ensure the safety of its transportation and storage. Transporting and storing a flammable gas safely is a challenge that many countries are actively researching[9].

Viegas (2021) states that the United Kingdom is exploring an innovative hydrogen gas storage method using nanoporous materials to contain the gas. Meanwhile, in the United States, compounds formed by metal alloys and hydrogen are used. These hydrides release the gas for consumption when subjected to high temperatures. The major challenge for H_2 compared to other more common fuel sources is its high cost[9].

Therefore, as crucial as reducing its production costs and improving efficiency is minimizing the logistical costs of its use. By reducing transportation and storage expenses, countries are pursuing new research avenues to further lower costs across the hydrogen supply chain, thus enhancing the cost-effectiveness of this clean energy source.

Green Hydrogen in the Econom

One significant economic aspect of green hydrogen (H_2V) is the production of green ammonia (NH_3V) and green methane. According to Lara and Richter (2023), NH_3V, in addition to having an even higher energy density than H_2, is simpler to store and is also an excellent biofuel option[7].

Brazil, for example, has one of the world's largest potentials for NH_3V production, especially if offshore wind generation is explored to provide the electricity needed for the electrolysis process. Whether in the steel industry or the transportation sector, the use of H_2V is a solution for carbon neutrality in various industrial complexes.

Aiming to capitalize on incentives for less polluting solutions, Viegas (2021) notes that many sectors are seeking to adopt cleaner energy sources. With the intense drive to reduce costs throughout production, distribution, and storage chains, the use of H_2V as a primary energy source is becoming a priority for the EU's carbon emission neutrality goals by 2050[9].

Saudi Arabia, for its part, is embarking on one of the world's largest H2V production projects, with an estimated budget of approximately 5 billion dollars for hydrogen production from wind and solar energy sourced from a vast region of the country.

Viegas (2021) adds that Saudi Arabia also aims to establish an economic zone through a planned city designed to accommodate 1 million residents, providing labor, infrastructure, economy, and tourism, all supported by this project, which is expected to become a global reference in clean energy production (CE)[9].

NH_3V and green methanol, resulting from the reaction of carbon dioxide (CO_2) with H2V, can help reduce greenhouse gas concentrations in the atmosphere.

Souza (2024) remarks that, although the production process for NH_3V is more expensive than ammonia derived from fossil fuels (FF), NH_3V is a clean alternative for reducing the greenhouse gases emitted during its production[10]. According to Macfarlane et al. (2020), with higher energy density per cubic meter than H_2V, the exploration of NH_3V is expected to increase starting in 2025, and it is forecasted to become cost-competitive by 2030[11].

Methanol, as noted by Lara and Richter (2023) and Mota et al. (2014), is the base component of many chemicals used in everyday life and is considered one of the most important. Whether in biodiesel production or CO2 hydrogenation, the methanol prevalent in the market comes from fossil fuels (FF) and natural gas (NG), and its production consumes a significant amount of energy[7; 12].

According to Gonçalves (2023), green methanol as a fuel has the potential to reduce CO2 emissions by up to 15%, which represents a significant decrease compared to gasoline, which has emissions between 65% and 95% of the same greenhouse gas. Gonçalves (2023) further highlights that, in addition to generating 3.71 billion dollars in 2021, the market expects this consumption to grow by 6% per year until 2030[8].

Whether as a fuel gas or synthetic fuel, as Lara and Richter (2023) argue, several pioneering countries are already defining strategies for this clean energy source. Germany, for example, not only has 32% of its energy matrix from wind sources but is also focusing on the implementation and promotion of H_2V to achieve success in its climate goals[7].

Green Hydrogen in Brazil

Europe, particularly after the onset of the war between Russia and Ukraine, found itself compelled to seek alternative gas suppliers. Brazil holds significant potential to supply up to 30% of European demand, for instance, if offshore wind energy were used for H_2V production.

Gonçalves (2023) add that in this offshore model, seawater could be utilized to produce H_2V after undergoing desalination. The growth of H2 as an energy source involves dense international cooperation, including facilitating support for both private and public financing. In Brazil, there are three main initiatives for H_2V production, located in Pecém (CE), Suape (PE), and Açu (RJ). According to Gonçalves (2023), these initiatives are focused solely on exportation and receive international investment for this purpose[8].

Forte and Gazillo (2023) emphasize that the Pecém port offers numerous strategic advantages to establish itself as a landmark in H2 production, both within Brazil and globally[6]. Whether due to its proximity to ports that can meet the needs of the United States or Europe, or its capacity to generate wind or solar energy, the Pecém region combines competitive advantages well-suited to host H_2V production and sales projects. H_2V represents a strategic opportunity for Brazil, considering its abundant renewable resources and the possibility of becoming a leader in the global clean energy market. With a favorable geographical location, particularly in the North and Northeast regions, where conditions for solar and wind energy generation are ideal, the country has all the necessary conditions to produce H_2V efficiently and sustainably.

Additionally, Brazil's energy sector infrastructure, with its extensive experience in renewable energy (RE), facilitates the incorporation of this technology, driving the advancement of a H2V production and distribution chain. This tool can become crucial for fostering a low-carbon economy and attracting international investments, consolidating Brazil's position on the global climate agenda[5; 7; 10].

Although there are challenges, such as initial investment and the need for specific public policies, these challenges are manageable and can be overcome. Technological advancements and the growing global demand for H_2V point to a reduction in production costs as the technology develops and scales up. Furthermore, the establishment of government incentives and international collaborations could attract new investors and build the appropriate infrastructure for generation and exportation. With continued support for research and innovation, Brazil is well-positioned to overcome these obstacles and emerge as a pioneer in the global transition to sustainable energy[5; 7; 10].

IV. Conclusion

This literature review has achieved its purpose of exploring the main barriers and possibilities related to H_2V production both in Brazil and globally. The use of a qualitative approach provided a deeper understanding of this complex phenomenon, highlighting the technological, economic, and environmental challenges, as well as the opportunities that arise from this context.

As outlined in the methodology, the careful selection of highly relevant scientific sources ensured a robust analysis that underscored the strategic potential of H2V in the energy transition. Not only were the obstacles to its implementation identified, such as the high production costs and the demand for appropriate infrastructure, but also the advantages that the use of this source can offer for the decarbonization of vital sectors and the diversification of the energy matrix.

Although the implementation of H_2V faces significant challenges—including high production costs, transportation and storage infrastructure, and the need for targeted public policies—technological advancements and the growing demand for clean energy have the potential to mitigate these difficulties. Brazil's geographical location is strategic, providing a strong foundation for the country to become a key global leader in H_2V production, particularly to meet the energy needs of foreign markets seeking alternative energy sources.

This study shows that international cooperation and government incentives are of great importance for the consolidation of an H_2V production chain. The need for continuous investments in research and innovation is crucial for overcoming obstacles and making H_2V a competitive and sustainable alternative in the long term.

Thus, the research demonstrates the perspective that H_2V can become a relevant solution to assist in achieving global climate goals and contribute to the socio-economic development of nations that believe in a renewable energy matrix. By identifying opportunities and challenges, this study lays the foundation for future investigations into incentive policies, technological improvements, and the integration of this energy into the global energy matrix.

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