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Review

Renewable energy perspectives: Brazilian case study on green hydrogen production

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Abstract: Hydrogen is recognized as a key component of the future renewable energy landscape. It can be sourced from diverse raw materials, including water, bioethanol, and microalgae. Despite its potential, challenges remain regarding its cost-effectiveness, infrastructure development, and integration into existing energy systems. This study evaluated Brazil's renewable energy production, focusing on resource availability, economic feasibility, technological challenges, and regulatory factors. Data from international energy agencies were analyzed using statistical indicators to compare Brazil's green hydrogen potential with global benchmarks. Findings indicate that Brazil's electrical matrix—comprising hydropower (59%), wind (13.2%), and solar (7%)—offers favorable conditions for large-scale green hydrogen generation. However, high production costs remain a limiting factor due to technological constraints, infrastructure gaps, and policy uncertainties. The results highlight Brazil's strong potential to become a key player in the green hydrogen market, provided that technological advancements, cost reductions, and regulatory frameworks evolve to support large-scale implementation. The study emphasizes the need for targeted investments, government incentives, and energy storage solutions to enhance Brazil's competitiveness in the global energy transition.

Keywords: low-carbon hydrogen; renewable energy; alternative fuels; Brazilian energy landscape

1. Introduction

Brazil, as a developing nation, presents substantial potential for growth in renewable energy, especially within the wind and solar sectors, paving the way for significant expansion in the upcoming years [1,2]. Within the scenario of renewable energies, hydrogen has been pointed out as one of the largest energy sources of the future, having paramount importance and versatility in the energy sector. Hydrogen can significantly enhance the efficiency of the oil industry and reduce greenhouse gas emissions, as its combustion produces only water as a by-product. Thus, applying hydrogen technologies is an alternative to further inserting renewable sources into the national energy balance.

Green hydrogen, produced from renewable sources like water, solar, wind, and hydro-energy through electrolysis, is increasingly recognized as crucial for reaching net-zero emissions by 2050 [3]. To address Brazil's potential for green hydrogen production, it is essential to consider not only the abundant renewable resources but also the recent socio-political and economic factors driving bioenergy and biofuel development in the country [4]. This transition aligns with global efforts to reduce greenhouse gas emissions, as replacing fossil fuels with advanced biofuels and green hydrogen can help mitigate climate change by lowering carbon emissions [4]. In this regard, the adoption of modern technologies—such as monitoring, optimization, and automation—has been identified as a key strategy to enhance energy efficiency and support the sustainable expansion of renewable energy [5,6].

Currently, the predominant method for green hydrogen production is water electrolysis, which involves breaking down water molecules using electrical energy. For hydrogen to be generated in a sustainable manner, the electricity used in electrolysis must originate from renewable sources such as hydroelectricity, wind, and solar power. Given Brazil's abundant renewable energy resources, assessing the potential for green hydrogen production through electrolysis within the current electrical framework is highly relevant.

Despite the established process for producing green hydrogen via electrolysis, considerable efforts are still required to scale up production to meet global demand [3]. Currently, the cost of green hydrogen remains higher than that of conventionally produced hydrogen, mainly due to technological and infrastructural constraints. However, as production scales, combined with potential carbon pricing policies and a gradual reduction in fossil fuel output, hydrogen is expected to become more competitively priced [3]. The development of robust guarantees of origin legislation will also be necessary to ensure the traceability and sustainability of hydrogen production as it becomes a more integral part of global energy systems.

Globally, the production and capacity for green hydrogen are rapidly advancing. In 2023, the worldwide installed capacity of water electrolyzers dedicated to hydrogen production reached 1.4 GW, with the new capacity added that year nearly equaling the cumulative global total up to 2022 [7]. This fast growth reflects an intensified commitment to green hydrogen technologies, underlining their potential to transition to cleaner energy sources. Additionally, global hydrogen production rose to 97 million tons (Mt) in 2023, a 2.5% increase over the previous year, demonstrating rising demand and production expansion. The majority of hydrogen production worldwide was obtained from fossil fuels (grey) emitting CO_2 to the environment. This upward trend in hydrogen production aligns with global energy strategies targeting a shift toward low-carbon alternatives and highlights green hydrogen's critical role in reducing reliance on fossil fuels.

This study examines Brazil's potential for advancing green hydrogen production within the broader context of renewable energy expansion. Given Brazil's abundant natural resources, particularly in hydroelectricity, wind, and solar energy, the nation is uniquely positioned to support green hydrogen production, a crucial element for sustainable energy transitions. Green hydrogen is produced through electrolysis powered by renewable energy, offering an alternative that minimizes greenhouse gas emissions compared to conventional hydrogen derived from fossil fuels. This study seeks to assess the feasibility and benefits of scaling up green hydrogen in Brazil, emphasizing the technological and infrastructural requirements essential for this shift.

To achieve these objectives, the study utilizes data from the International Renewable Energy Agency (IRENA), the International Energy Agency (IEA), and Empresa de Pesquisa Energética (EPE). These data are analyzed using statistical indicators to evaluate Brazil's green hydrogen potential in comparison to global benchmarks. Key metrics such as energy production capacity, cost-effectiveness, and technological feasibility are assessed. Additionally, insights from scientific databases like Scopus and Web of Science are reviewed to contextualize findings within the broader renewable energy landscape. By integrating these analyses, the study provides a comprehensive assessment of green hydrogen's role in Brazil's energy portfolio and offers evidence-based recommendations for its development.

The data obtained from IRENA, IEA, and EPE are examined to assess Brazil's renewable energy potential in the context of green hydrogen production. The analysis involved comparing Brazil's renewable energy capacity and production trends with global benchmarks, particularly regarding the availability of hydropower, wind, and solar resources. Additionally, the study reviewed projections from energy planning reports to evaluate Brazil's positioning in the global energy transition.

The structure of the remainder of this article is as follows: Section 2 examines Brazil's renewable energy landscape, focusing on the roles of hydropower, solar, and wind in the country's sustainable energy transition. Section 3 explores the energy perspectives related to green hydrogen production in Brazil. Section 4 discusses the study's findings, covering implications for energy policy and including subsections on technological challenges, infrastructure needs, and economic considerations. Finally, Section 5 concludes the article by summarizing key insights, addressing the study's limitations, and suggesting directions for future research in Brazil's energy sector.

2. Brazil's renewable energy landscape: The role of hydropower, solar, and wind in a sustainable energy transition

According to the Brazilian Energy Balance reported by the Empresa de Pesquisa Energética (2024), hydropower remains Brazil's dominant source of electricity generation, accounting for a significant share of the country's energy mix in 2023. This reliance on hydropower in the electricity matrix highlights Brazil's strengths in renewable resources and the potential for further diversification into other renewables, such as solar and wind, to ensure a resilient and sustainable energy future. However, within the total energy matrix, hydropower represents only around 12.1%, as shown in Figure 1, indicating that this source could be more fully explored in this sector.

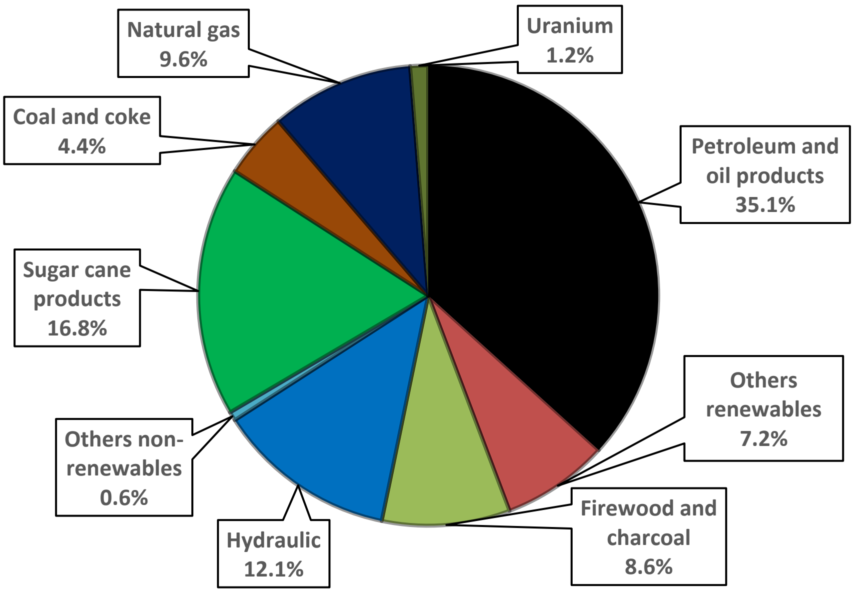

Figure 1. Internal energy supply by source in 2023. Data from [8].

In the Brazilian energy landscape, although non-renewable sources still account for a larger share of overall consumption, the country stands out globally with its comparatively high reliance on renewable sources [8]. Adding derivatives of sugarcane, hydraulics, firewood and charcoal, and other renewables, these sources contribute 44.7% to Brazil's total energy supply—nearly half of the country's total energy matrix. This figure reflects the total internal energy supply, not just electricity generation. This reliance on renewables highlights a contrast with global trends, where the use of renewable energy is generally lower.

Despite the notable share of renewables, there is significant potential for further growth, driven by Brazil's abundant natural resources. Hydropower, solar, and wind energy have substantial unexplored capacities, positioning the country to reduce climate-related risks and contribute to sustainable development. The internal energy supply survey highlights a steady expansion in renewable energy infrastructure. For instance, between 2012 and 2023, there was notable growth in installed hydroelectric generation capacity, with an even more significant increase in solar and wind power installations, as shown in Figure 2. This stable progression underscores Brazil's potential to further expand its renewable energy capabilities.

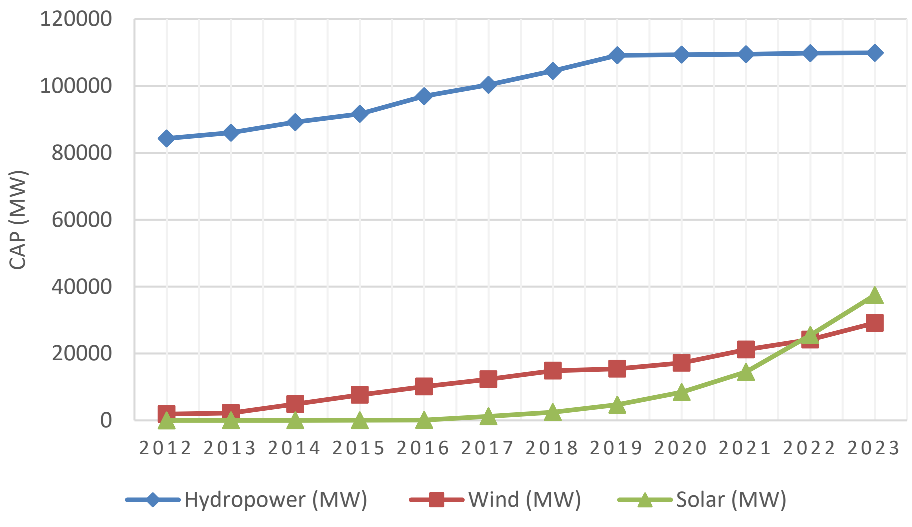

Figure 2. Evolution of hydropower, wind, and solar energy capacity in Brazil. Data from [9,10].

The upward trend in renewable energy capacity underscores Brazil's commitment to diversifying its energy portfolio. Hydropower remains a dominant source, yet the marked increase in wind and solar installations signals a strategic move toward a more balanced and resilient renewable infrastructure. This expansion allows Brazil to capitalize on its abundant natural resources while also strengthening its resilience to climate challenges. This foundational growth in clean energy not only reinforces Brazil's leadership in sustainable development but also sets the stage for a deeper analysis of the Brazilian electrical scenario, with a particular focus on hydropower, solar, and wind sources.

2.1. Brazilian electrical scenario

In 2023, Brazil's electricity generation in public service plants and auto producers totaled 708.1 TWh, marking a 4.6% increase compared to 2022 [8]. Renewable energy sources played a dominant role, contributing 72.3% of the total electricity generated, with hydropower as the largest contributor, as described in Figure 3. Hydroelectric power alone accounted for approximately 59% of the domestic energy supply, followed by wind at 13.2%, solar at 7.0%, and sugarcane bagasse at 5.1%. This strong reliance on renewable resources reflects Brazil's commitment to a sustainable energy matrix, although there remains significant potential for further diversification.

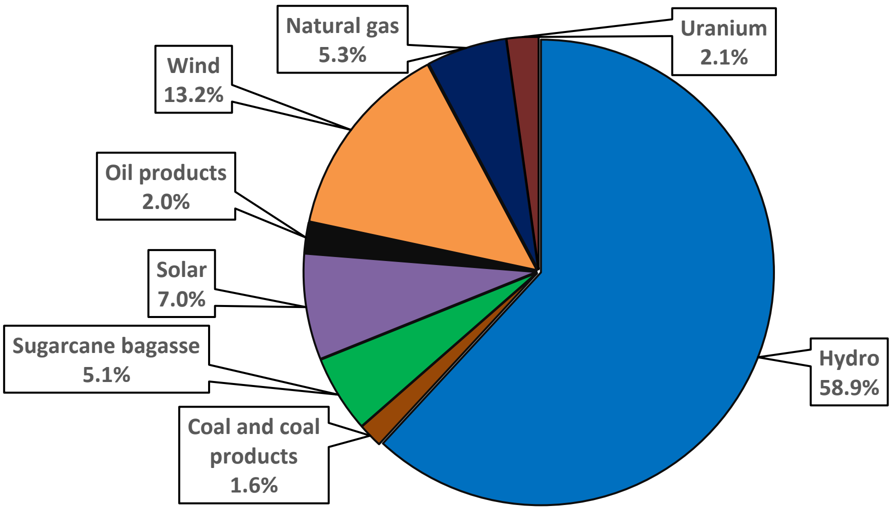

Figure 3. Total electricity supply by source in 2023. Data from [8].

Brazil has a notably high share of renewable energy in its total energy supply, although countries like Norway and Iceland have even higher percentages. Nevertheless, Brazil stands out as a global leader in biofuel production. This favorable energy profile, combined with the country's rich natural reserves and biodiversity, creates ideal conditions for developing green hydrogen technology from electrolysis. Thus, it becomes relevant to separately evaluate the growth potential of hydro, wind, and solar energy in the national scenario.

2.1.1. Hydroelectricity

According to Empresa de Pesquisa Energética (2024), Brazil's hydroelectric potential is approximately 246.24 GW, with 44% of this capacity currently in operation. The northern region of Brazil concentrates the largest share of hydro potential, equivalent to 98.55 GW of integrity [8], largely concentrated in the state of Amazonas. This state is home to an expansive hydrographic basin, covering over 7 million km², being rich in biodiversity, and containing extensive mineral resources that attract considerable industrial interest [11], as illustrated in Figure 4.

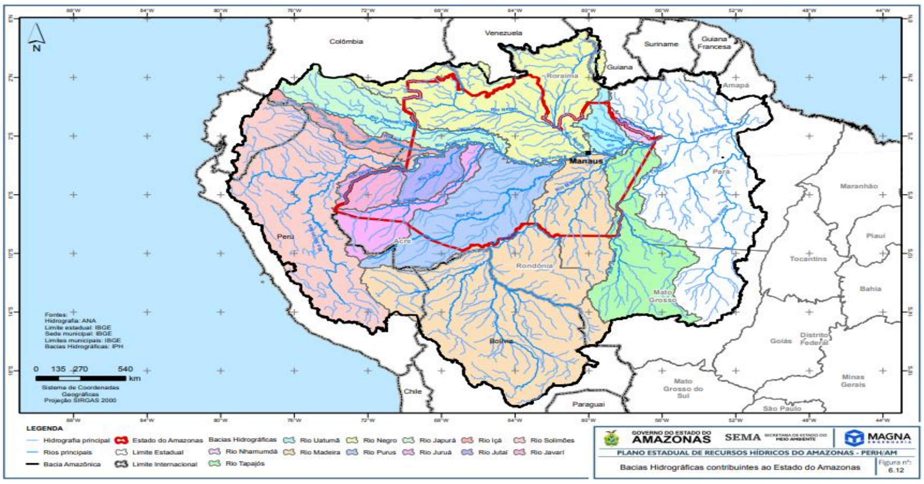

Figure 4. State water resources plan—PERH/AM [11].

Brazil is home to some of the world's largest hydroelectric dams, including the Itaipu Dam on the Paraná River, bordering Paraguay, with a capacity of 14,000 megawatts (MW), making it the second largest globally. The Belo Monte Dam on the Xingu River (11,233 MW, fourth largest) and the Tucuruí Dam on the Tocantins River (8370 MW, sixth largest) further highlight Brazil's significant hydroelectric infrastructure. These major installations are concentrated mainly in the Midwest, South, and Southeast regions [12,13]. Consequently, as Brazil progresses toward sustainable development, hydroelectricity's role in supporting electrolysis for hydrogen production could be further enhanced, maximizing the country's hydraulic potential.

2.1.2. Wind energy

The Brazilian electrical matrix is decentralized and based on renewable sources; in this sense, wind energy has been the most competitive in recent energy auctions. The use of wind energy is socially, environmentally, and economically beneficial if its goal is a more sustainable future and compliance with the Climatic Agreement. The wind farm is considered a source of clean energy production, takes up little physical space, can generate power in remote places, and is abundant because wind is available all over the world [14].

Table 1 summarizes the results for gross, technical, and environmental and social potentials of wind energy in Brazil. The table presents three key metrics: the area in square kilometers (km²), potential capacity in gigawatts (GW), and the share of the gross wind resource area in percentage (%). The gross potential represents the total wind resource area, while the technical potential accounts for areas suitable for wind energy development considering technological constraints. The environmental and social potential further refines this by excluding areas with significant environmental or social restrictions.

Table 1. Results summary for gross, technical, and environmental and social potentials.

Potential	Area (km²)	Potential capacity (GW)	Share of the gross wind resource area (%)
Gross	562,522	1688	100
Technical	354,735	1064	63
Environmental and social	110,159	330	20

Source: [15].

The years 2021 and 2022 presented significant challenges for Brazil's wind energy sector, largely due to the COVID-19 pandemic's impact on the economy. Despite these obstacles, the sector demonstrated resilience as signs of economic recovery emerged. Data from the Central Bank of Brazil (BCB) and the Brazilian Institute of Geography and Statistics (IBGE) indicate that Brazil's Gross Domestic Product (GDP) expanded by approximately 7.6% over these two years, accompanied by a 5.66% increase in electricity consumption, signaling a rebound in demand and growth across the energy sector.

Brazil's wind power has grown strongly over the past decade, rising from 1 GW in 2011 to 21 GW in January 2022. Today, wind is the country's second-largest energy source, accounting for 13.2% of the electricity matrix [8]. Regarding this growth, three factors became decisive: first, the regulatory framework of auctions facilitated the purchase of wind energy at a competitive price; second, a nationally focused financial project provided Brazil with a strong industrial wind base capable of producing enough turbines to install approximately 5 GW per year; and third, there was growing uncertainty about the role of hydroelectric power in the electric matrix due to changes in climatic conditions and the decrease in the reservoirs necessary for the production of hydroelectric energy [15,16].

In line with projections from EPE's Ten-Year Energy Expansion Plan (2022), wind energy is anticipated to play a transformative role in Brazil's energy matrix throughout this decade [17]. This growth is underscored by recent achievements: in 2023, Brazil's wind energy production reached 95.8 TWh, marking a 17.4% increase over the previous year's 81.6 TWh [8]. Alongside this rise in generation, installed wind power capacity expanded by 20.7%, totaling 28,664 MW by year-end, as reported by the Generation Information System (SIGA) of the National Electric Energy Agency (ANEEL). Such progress highlights wind energy's significant contribution to meeting the country's expanding energy demands.

Moreover, wind energy, alongside solar power, has become central to the expansion of Brazil's electricity supply, particularly through offshore wind resources. Figure 5 indicates that wind farms are predominantly located in rural and low-density population areas, as wind flow in urban centers is slower due to the high number of physical obstructions [18]. Consequently, wind power's increasing role not only strengthens Brazil's renewable energy portfolio but also offers new opportunities for green hydrogen production via electrolysis, further aligning with economic and environmental objectives to stabilize the national energy system.

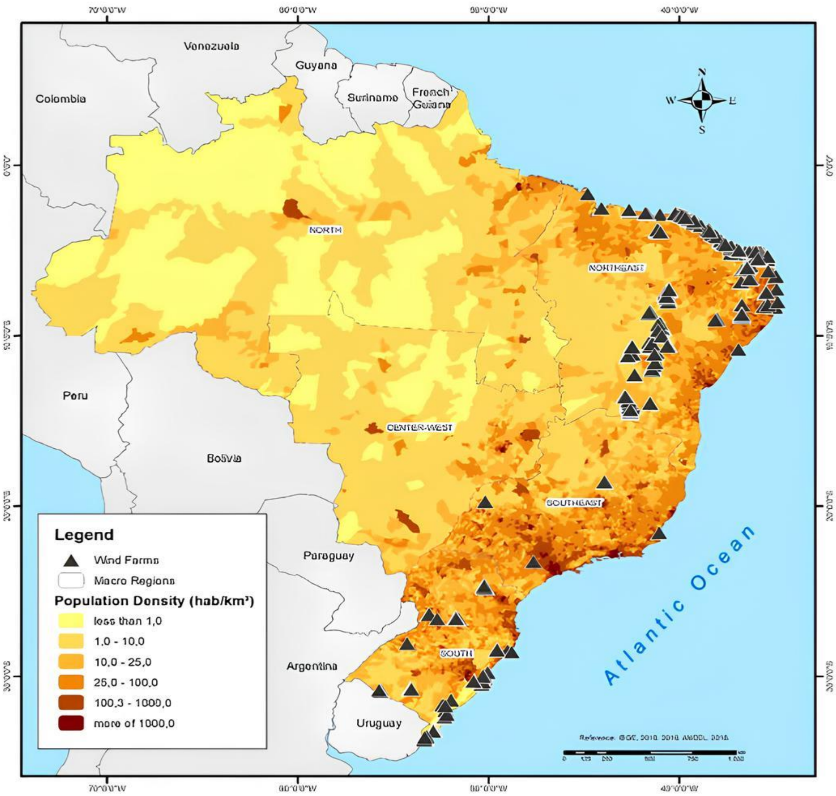

Figure 5. Wind farms in operation in Brazil [18].

2.1.3. Photovoltaics

Brazil's regulatory measures, such as the "Net Metering" policy, have actively encouraged the growth of micro- and mini-distributed generation of electricity. This policy allows smaller energy systems to receive compensation for any surplus energy they produce, which has incentivized expansion across the sector. By 2023, micro- and mini-distributed generation reached an impressive 30,950 GWh, with an installed capacity of 26,627 MW [8]. Solar photovoltaic energy was the dominant source within this framework, generating 29,813 GWh and contributing 26,366 MW to the country's installed capacity [8]. This distributed approach not only supports energy resilience but also aligns well with Brazil's increasing demand for localized, sustainable energy solutions.

Solar energy is equally vital for Brazil's green hydrogen production efforts through electrolysis, given the abundant solar resources available, particularly in the northeast and central regions. These areas, which already host several power plants, still hold vast untapped potential, aligning with the decennial energy plans of Brazil's Ministry of Energy that emphasize sustainability, cost reduction, and energy diversification [17,19]. As shown in Figure 6, regions with high population densities also experience some of the highest solar radiation levels, creating a favorable landscape for photovoltaic energy within distributed micro- and mini-generation systems. This geographical synergy, coupled with proximity to distribution networks and high local demand, positions solar energy as a critical component in Brazil's transition toward a more decentralized and sustainable energy matrix [20,21].

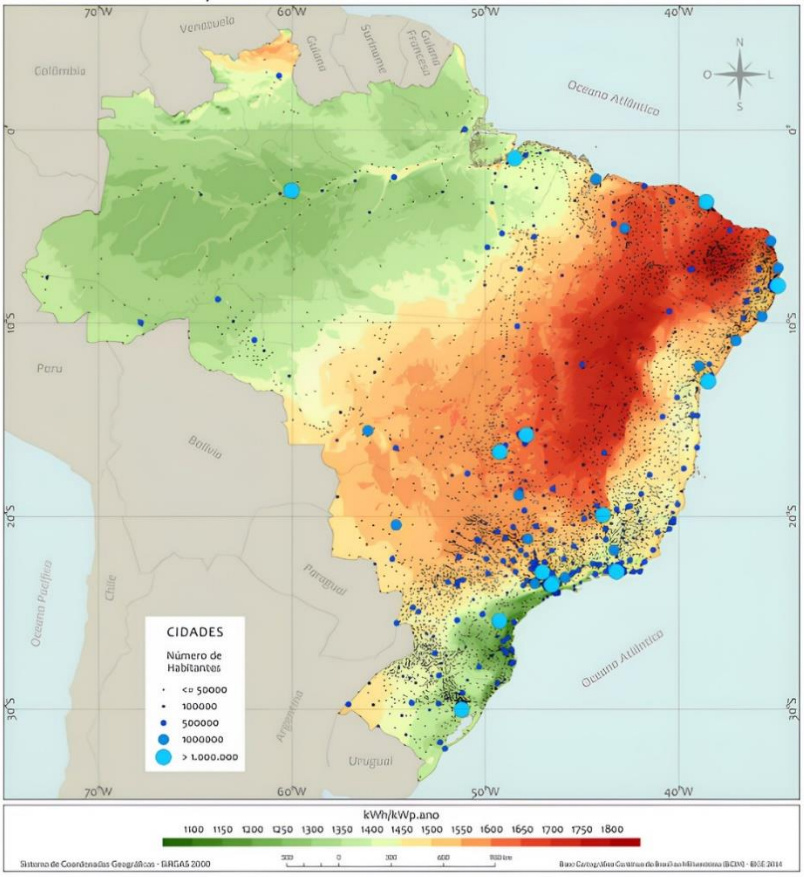

Figure 6. Photovoltaic generation potential: solar radiation and population [21].

Brazil's abundant silicon reserves—critical for solar panel production—together with extensive land areas and high levels of solar radiation, provide a strong foundation for solar energy expansion. These resources enable the country to significantly scale up solar electricity generation, with the potential to produce tens of thousands of gigawatt-hours from this renewable source alone [19]. Furthermore, Brazil's favorable geographic and climatic conditions, such as consistent sunlight throughout the year, enhance its capacity for sustainable energy diversification. This positions Brazil well to achieve energy independence and support environmental goals through a robust increase in solar energy output.

2.2. Energy storage for renewable integration in Brazil

The increasing penetration of variable renewable energy sources, such as wind and solar, in Brazil's energy mix necessitates the development of robust energy storage solutions [22]. Given the intermittent nature of these sources, energy storage systems play a crucial role in ensuring grid stability, improving reliability, and enabling a higher share of renewables in the national electricity system [22–24]. As a result, investing in diverse and scalable storage solutions will be key to supporting Brazil's transition toward a more resilient and sustainable energy future.

Pumped hydro storage remains the dominant large-scale energy storage technology globally and in Brazil. The country possesses significant hydroelectric infrastructure, which provides opportunities for converting existing reservoirs into pumped storage facilities [22]. This approach enhances grid flexibility by allowing energy to be stored during periods of low demand and released during peak demand [23].

Brazil's hydropower-dominated energy sector offers a natural advantage for pumped hydro storage development. The feasibility of retrofitting existing hydro plants for pumped storage has been widely studied, and potential projects could support the increasing share of intermittent solar and wind generation [22]. However, environmental regulations, water resource management constraints, and financial barriers pose challenges to the rapid expansion of this technology [23].

Battery storage technologies, particularly lithium-ion batteries, have gained prominence in Brazil as a solution for short-term energy balancing and grid services [24]. The declining costs of battery storage systems have made them increasingly viable for integration with renewable energy sources, both at the utility scale and for distributed energy systems [24].

Despite cost reductions, battery storage in Brazil faces economic and regulatory challenges. The high initial investment required for large-scale deployment and the need for supportive policies to incentivize adoption remain key concerns [23]. Furthermore, the reliance on imported lithium-ion battery components introduces supply chain vulnerabilities [24]. Local research and investment in alternative battery chemistries, such as sodium-ion and flow batteries, could provide long-term solutions tailored to Brazil's needs [24].

Looking ahead, Brazil has significant potential to expand its energy storage capabilities. The synergy between its hydropower assets and emerging battery technologies can create a more resilient and flexible power system, supporting the continued growth of solar and wind energy. Investments in research, regulatory improvements, and infrastructure development will be essential for unlocking the full potential of energy storage in Brazil's sustainable energy transition.

3. Energy perspectives of green hydrogen production in Brazil

Brazil follows the global trend of hydrogen production through the reform of natural gas, focusing on the refining and fertilizer sectors that generally use processes with high carbon dioxide emissions [25]. Moreover, Brazil's hydrogen production landscape encompasses various methods, including fossil fuel-based processes, biomass utilization, and water electrolysis [26]. In 2023, global hydrogen production reached 97 Mt, with nearly all of it derived from unabated fossil fuels [27]. China remains the largest producer of hydrogen worldwide. However, truly green hydrogen—produced via electrolysis using renewable electricity—represented only about 1% of global hydrogen production [27], highlighting the need for cleaner production pathways to support a sustainable energy transition.

Most hydrogen production facilities in Brazil are located in coastal regions near the natural gas pipeline network [28]. Currently, the predominant source of hydrogen production occurs within oil refineries, utilizing methane-reforming techniques, with a particular emphasis on steam reforming [1,26]. Petrobras data, from the Brazilian petroleum industry, reveals that more than 70% of Brazilian refineries, including facilities such as Paulínea and Mataripe plants, play a significant role in hydrogen production, primarily catering to internal processes within the oil refining sector. The hydrogen production capacity of these refineries is approximately 19 million (Nm^3H_2/day) [29].

Several studies have been conducted in the literature on the technical-economic analysis of hydrogen production using other renewable sources, such as hydro, wind, solar, and biomass [1,30–32]. Shi, Qian, and Yang (2020) analyzed a wind-solar energy system integrated with large-scale hydrogen production, finding that its operational cost is approximately $3.59 per kilogram of hydrogen, comparable to coal gasification combined with carbon capture technology [33]. Yadav and Banerjee (2018) assessed the economics of hydrogen production using solar-driven high-temperature steam electrolysis. They found that, for a photovoltaic plant, hydrogen production costs range from $16 to $22 per kilogram, depending on electrolyzer operating conditions [34]. Nadaleti, Santos, and Lourenço (2020) examined the economic viability of hydrogen production utilizing surplus energy from Brazilian hydroelectric dams and wind farms. They determined that hydrogen production is economically feasible but comes at a higher cost of 0.303 USD per kilowatt-hour compared to wind and hydroelectric plants [35].

Another process currently representing a viable alternative to fossil fuels is thermochemical conversion, which involves heat-driven chemical reactions to transform raw materials (e.g., fossil fuel and biomass). Despite being the costliest methods for hydrogen production at present, electrolysis and thermochemical processes represent feasible alternatives to fossil fuels. Their integration with other energy sources demonstrates substantial potential for sustainable development [36].

Efforts to increase the use of green hydrogen for energy transition are increasing in many countries, emphasizing larger-scale, more energy-friendly electrolysis [37]. In this scenario, Brazil has a prominent position to become an exporter of low-carbon hydrogen since it presents excellent and favorable climatic conditions for the generation of electricity through wind, solar, and hydro sources [32]. As noted in Figure 7, there has been an exponential growth trend in the scale of projects over the last few years.

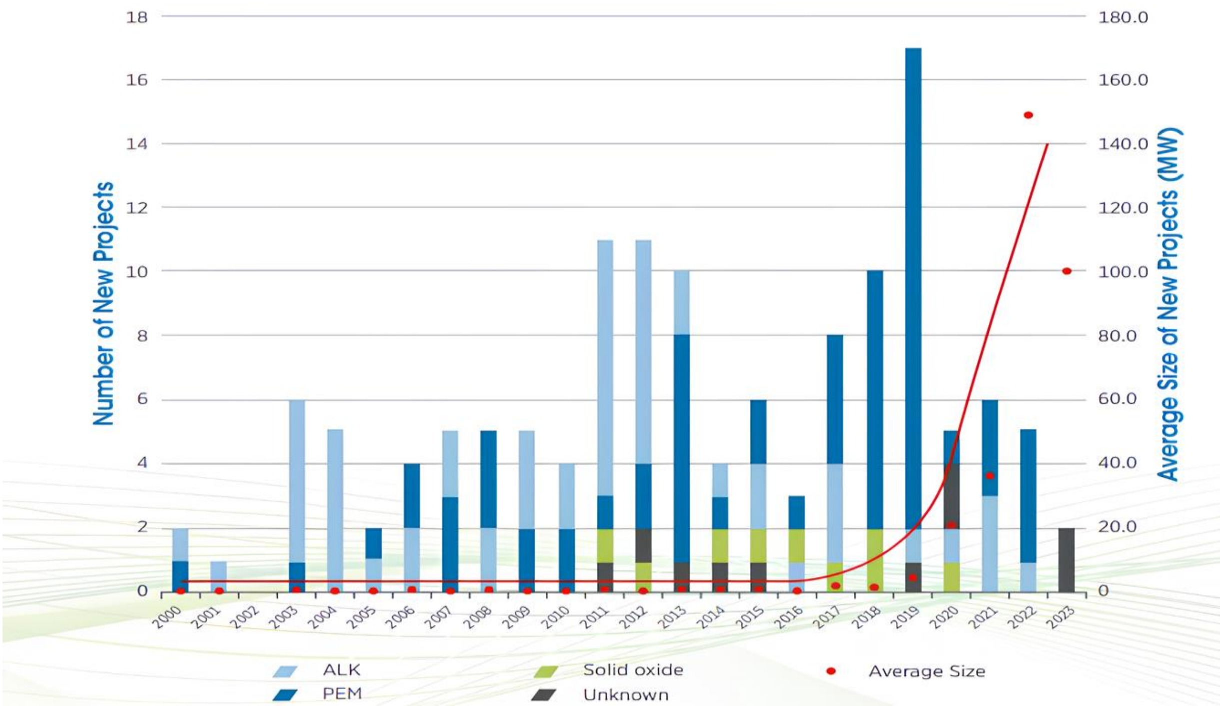

Figure 7. Timeline of power-to-hydrogen projects by electrolyzer technology and project scale [37].

The expenses associated with generating clean energy remain relatively high in Brazil. However, the development of novel technologies can potentially enhance affordability, fostering competitiveness with other energy sources and bolstering safety and diversification within the Brazilian energy landscape [35]. To mitigate the costs of producing green hydrogen, reducing the expenses of generating the energy needed for electrolysis is imperative in both the short and long term.

3.1. Production costs and competitiveness

The cost of producing green hydrogen in Brazil varies depending on the energy source, scale, and technological efficiency. Estimates suggest that production costs range between USD 2.50 and USD 6.80 per kilogram, influenced by factors such as the number of operational hours of renewable plants and the electrolyzer capital expenditure (CAPEX) of electrolysis systems [38]. In comparison, regions with favorable renewable energy conditions, such as the Middle East, Australia, and the United States, report production costs between EUR 3 and EUR 5 per kilogram, while in Europe, costs can reach EUR 8 per kilogram due to higher electricity prices and infrastructure expenses [38].

An alternative approach to large-scale hydrogen production is the utilization of surplus energy from hydroelectric and wind farms, which can reduce costs by leveraging excess generation that would otherwise go unused. Studies indicate that hydrogen produced from surplus energy in Brazil has an estimated cost of USD 0.303 per kilowatt-hour (kWh) [35]. However, this is still more expensive than hydroelectric power (USD 0.05/kWh) and wind energy (USD 0.10/kWh), highlighting the need for further cost reductions and efficiency improvements [1].

A major challenge for green hydrogen production in Brazil is the high cost of capital, which affects investments in renewable energy infrastructure. In emerging markets, financing costs tend to be higher than in developed economies. For instance, the cost of capital for solar photovoltaic (PV) projects in Brazil and Mexico ranged between 10.5% and 12% in 2022, compared to significantly lower rates in developed markets [27]. This financial constraint increases overall project costs, potentially slowing down the expansion of green hydrogen initiatives.

Despite these challenges, Brazil has made substantial progress in solar PV infrastructure development, starting with the ANEEL initiatives in 2011. These efforts have contributed to advancing PV technology and expanding renewable energy capacity. As a result, Brazil's solar PV potential now exceeds that of some European countries, reinforcing the country's long-term capability to support cost-competitive hydrogen production [27].

Although low-emission hydrogen remains expensive in the short term, costs are expected to decline significantly due to technological advancements, economies of scale, and improved financial conditions [27]. A critical factor for economic viability is the reduction in CAPEX for electrolysis technologies and the increasing operational hours of renewable energy plants. Some studies indicate that for hydrogen production to become economically competitive, electrolysis plants must operate for more than 3,000 hours per year and electrolyzer CAPEX must decrease below USD 650/kWe [38].

Brazil's abundant renewable energy resources, combined with its expanding solar and wind energy sectors, provide a strong foundation for developing a competitive green hydrogen market. However, achieving this potential will require reducing financing costs, improving regulatory frameworks, and increasing investments in infrastructure. Addressing these aspects will be essential for positioning Brazil as a key player in the global hydrogen economy.

3.2. Addressing technological and infrastructural challenges

While Brazil has abundant resources to produce green hydrogen, several technological and infrastructural challenges must be addressed. The electrolysis process, though promising, remains energy-intensive and requires substantial capital investment. Ensuring a steady and cost-effective supply of renewable electricity for electrolysis will be critical for the success of green hydrogen initiatives. Additionally, the development of storage and transportation infrastructure is paramount. The storage and distribution of green hydrogen present significant technical challenges due to its low energy density and the need for specialized infrastructure.

One example of ongoing efforts to develop large-scale green hydrogen infrastructure in Brazil is Unigel's 60 MW electrolysis project for ammonia production. This initiative aligns with Brazil's National Fertilizer Plan 2050, which aims to strengthen domestic ammonia production capacity and reduce reliance on imports. The plan sets ambitious targets, including the production of 1.9 million tons per annum (Mtpa) of nitrogen (2.3 Mt NH_3-eq) by 2030, a 50% reduction in fertilizer imports by 2040, and the establishment of at least three low-emissions ammonia plants by 2050 [27]. Ammonia plays a crucial role in the global hydrogen supply chain, as it is one of the most efficient hydrogen carriers due to its higher energy density and ease of storage compared to liquid hydrogen. The development of ammonia-based hydrogen infrastructure in Brazil could not only support domestic industrial demand but also mitigate the logistical barriers associated with hydrogen export, making transportation over long distances more viable.

Despite these advancements, large-scale hydrogen exports remain constrained by the need for specialized storage, conversion, and transportation solutions. Shipping hydrogen in liquid form requires cryogenic temperatures below −253 °C, posing significant technical and economic challenges [27]. Alternatively, exporting hydrogen in the form of ammonia—where it can be reconverted to hydrogen at the destination or used directly in industrial applications—offers a more practical solution. However, this approach requires further investment in conversion technologies and port infrastructure capable of handling ammonia safely at a large scale. Without such developments, Brazil's potential as a global green hydrogen supplier may remain limited.

Moreover, the successful integration of green hydrogen into Brazil's energy portfolio will depend on strong policy frameworks that support the scaling up of hydrogen production. The establishment of clear regulations, incentives for research and development, and financial support for green hydrogen projects will be essential for attracting investment and fostering innovation in this sector.

3.3. Prospective scenarios and energy modeling for renewable energy in Brazil

Brazil has been strengthening its position in the global hydrogen economy through strategic investments and policy initiatives. A key development is the USD 3.8 million research and development (R&D) investment by Petrobras to assess the feasibility of natural hydrogen extraction within Brazil. This initiative, which began operations in October 2023, is expected to provide insights into the potential of naturally occurring hydrogen reservoirs and their integration into Brazil's energy matrix [27]. These efforts could enhance Brazil's energy diversification and support its transition to a low-carbon economy.

In addition to electrolytic hydrogen production, Brazil is also exploring alternative pathways, such as bioethanol reforming. A demonstration project is currently assessing the viability of converting bioethanol into hydrogen, leveraging the country's extensive ethanol industry. Given that most bioethanol plants are located in the center and southwest regions, this approach could enhance regional hydrogen supply while integrating existing biofuel infrastructure into the hydrogen economy.

In parallel, the country is advancing its commitment to sustainable aviation fuels (SAF) through the RenovaBio program and the National Aviation Biofuel Program (ProBioQAV). These initiatives align with the Fuel of the Future Act, passed by Congress in September 2024, which introduces a greenhouse gas (GHG) reduction target of 1% by 2027, increasing to 10% by 2037 [27]. This legislative framework is projected to drive SAF demand, particularly for biofuels derived from hydroprocessed esters and fatty acids (HEFA). Additionally, Brazil's 2031 ten-year energy expansion plan anticipates SAF uptake reaching 1.4% by 2031, reinforcing the country's role in decarbonizing the aviation sector [27].

Brazil is also advancing in the maritime sector with the establishment of a Marine Fuels Subcommittee under the Fuel of the Future Act. This initiative aims to promote the adoption of low-carbon alternatives in maritime transport, ensuring alignment with international shipping decarbonization efforts [27].

Infrastructure development remains a crucial aspect of Brazil's green hydrogen strategy. The Climate Investment Fund has allocated USD 70 million to the industrial and port complex in Pecém to develop shared hydrogen infrastructure and an innovation center dedicated to renewable hydrogen. These investments are expected to facilitate large-scale hydrogen production, enhance export capacity, and attract further private-sector engagement [27].

Additionally, since the publication of the Global Hydrogen Review 2023, Brazil has secured substantial international funding for hydrogen infrastructure. The World Bank has provided USD 135 million for hydrogen-related projects, and this amount may be further increased following a Memorandum of Understanding (MoU) signed at COP 28. The agreement foresees an additional USD 1 billion in funding for hydrogen-related developments in Brazil, positioning the country as a key player in the global hydrogen supply chain [27].

Brazil's long-term energy planning has also reinforced its transition toward a low-carbon economy. Policies such as the 2010–2019 Plan for Energy Expansion reflect the country's commitment to reducing fossil fuel dependency while expanding hydro and wind energy integration into the national grid. These structured policies, combined with ongoing investments, indicate a favorable trajectory for Brazil to scale up green hydrogen production and contribute to global decarbonization efforts [39].

Brazil's position in the global hydrogen economy is further strengthened by its iron and steel industry. The country holds the largest iron ore deposits in Latin America, which support both domestic steel production and significant export activities [27]. As demand for direct reduced (DR)-grade iron ore increases, particularly for low-carbon steelmaking, Brazil's hydrogen production capabilities could be pivotal in supplying clean hydrogen for green steel manufacturing. The mining company Vale, for instance, anticipates a long-term shift in demand toward high-grade iron ore suitable for hydrogen-based steel production, reinforcing Brazil's strategic role in the decarbonization of the global steel sector [27].

The electricity demand for electrolytic hydrogen production in Latin America and the Caribbean is expected to grow significantly by 2030, driven by announced projects in several countries [27]. This demand will depend on the availability of renewable energy sources, particularly hydropower, wind, and solar photovoltaic PV. Countries with a high share of renewable electricity in their generation mix will have a strategic advantage in producing low-carbon hydrogen. Brazil, for instance, has announced the potential production of over 2 Mtpa of hydrogen by 2030, with more than 1 Mtpa when excluding projects still at very early stages [27]. Understanding the current electricity generation landscape in the region is crucial to assessing the feasibility and sustainability of these hydrogen production goals.

If all announced projects are successfully implemented, annual electrolytic hydrogen production in Latin America could exceed 7 Mt of hydrogen by 2030 [27]. Brazil is expected to play a central role in this expansion due to its abundant renewable energy resources and existing industrial infrastructure, which can support large-scale hydrogen production.

Figure 8 presents the electricity generation mix in selected countries of Latin America and the Caribbean in 2022, along with the estimated equivalent electricity share required for announced hydrogen projects by 2030. The chart highlights the proportion of hydropower (blue), wind and solar PV (green), and other energy sources (gray) in each country's electricity generation. The white circles indicate the electricity consumption needed for hydrogen production relative to total electricity generation. Notably, countries with a high share of hydropower, such as Paraguay and Brazil, or a strong presence of solar and wind energy, like Uruguay, are better positioned to meet future hydrogen demand using renewable sources.

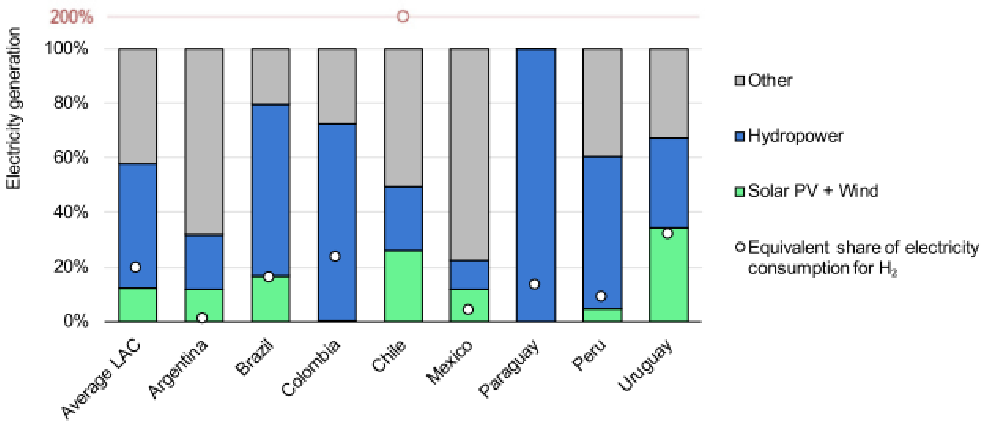

Figure 8. Potential electricity demand for electrolytic hydrogen production from announced projects in Latin America and the Caribbean, 2030, and electricity generation, 2022 [27,40].

4. Discussion

Hydrogen has gained increasing attention in global energy discussions, particularly in the G7 and G20. Within this context, Brazil's G20 Presidency has prioritized innovative approaches to sustainable fuels, including hydrogen and biofuels, under the Energy Transitions Working Group. This aligns with Brazil's broader commitment to renewable energy expansion and its potential to emerge as a key green hydrogen supplier [41].

To support its renewable energy development, Brazil has implemented various policy instruments. One notable example is the Alternative Sources Incentive Program (PROINFA), which has played a crucial role in promoting the integration of renewable energy sources into the national grid [41]. Additionally, governmental bodies such as the National Energy Policy Council (CNPE) and the Ministry of Mines and Energy (MME) have been pivotal in formulating and enforcing energy policies that drive sustainable transitions [41].

The National Biofuels Policy (RenovaBio), launched in 2017, has further reinforced Brazil's commitment to decarbonization. This initiative has stimulated biofuel production while introducing a cap-and-trade system for decarbonization credits (CBIOs), incentivizing cleaner energy alternatives [42]. Moreover, Brazil's long-term energy planning frameworks, including the Energy National Plan (ENP) and the Decadal Plan for Energy Expansion (PDE), outline strategic pathways for sustainable energy development, ensuring that national energy policies align with international climate goals [43].

Brazil has also strengthened its international partnerships to advance its role in the hydrogen economy. The recent MoU signed with Germany and the European Union underscores Brazil's strategic position as a potential supplier of green hydrogen to meet Europe's growing demand. Germany's National Hydrogen Strategy projects a requirement of 90–110 TWh of green hydrogen by 2030, creating opportunities for energy-exporting countries like Brazil.

Additionally, the European Union has been refining its regulatory framework to promote sustainable hydrogen imports, reinforcing the significance of partnerships with nations rich in renewable energy resources [31]. These agreements enhance Brazil's potential to integrate into global hydrogen value chains while fostering technological collaboration and investment in clean energy infrastructure.

Despite these policy advancements, challenges remain in ensuring effective implementation and enforcement. While initiatives such as PROINFA have facilitated the growth of renewable energy and contributed to Brazil's ambitious greenhouse gas reduction targets, further efforts are needed to address regulatory barriers, technological constraints, and environmental concerns associated with large-scale energy projects [41]. Overcoming these challenges demands stronger policies, regulatory stability, and sustained investment in innovation.

4.1. Brazil's renewable energy capacity

Brazil's renewable energy mix is one of the most impressive in the world, with hydropower, wind, and solar energy playing dominant roles. The country's electricity grid is primarily powered by hydropower, contributing around 59% of its total electricity consumption. This strong foundation in hydroelectric power provides Brazil with an excellent starting point for expanding green hydrogen production through water electrolysis. However, the continued growth in solar and wind power is equally crucial to this transition. The fast expansion of solar and wind installations underscores the country's potential to diversify its energy mix, reducing its dependency on hydropower and increasing the resilience of the energy system.

Wind energy, in particular, has seen remarkable growth in recent years, now accounting for 13.2% of Brazil's total electricity generation. Brazil's favorable wind conditions, particularly in the northeast and offshore areas, provide a significant opportunity to scale up the use of wind energy for green hydrogen production. The global trend toward renewable energy and green hydrogen is accelerating, and Brazil is well-positioned to leverage its wind potential to meet both domestic and international demand for hydrogen. Additionally, the expansion of solar energy, particularly in the northeast, complements the wind sector and strengthens the potential for green hydrogen production through electrolysis.

4.2. Green hydrogen as a strategic alternative

Hydrogen is seen as one of the most promising solutions for decarbonizing the global energy system. Green hydrogen, produced using renewable electricity for electrolysis, stands out as a clean alternative to conventional hydrogen, which is derived from fossil fuels. Brazil's abundance of renewable energy resources, particularly hydropower, wind, and solar, makes it an ideal location for scaling up green hydrogen production. The use of green hydrogen to replace or supplement conventional hydrogen can play a pivotal role in Brazil's energy transition by significantly reducing greenhouse gas emissions, especially in industrial sectors like oil and gas, which are traditionally energy-intensive.

Beyond hydrogen production for fertilizers, Brazil and other Latin American countries, such as Mexico, Argentina, Peru, and Chile, have significant potential to contribute to the global near-zero emissions steel market. A key example is the collaboration between the Brazilian mining company Vale and Stegra (formerly H2 Green Steel) in Sweden, where Vale will supply iron ore pellets for a 100% hydrogen-based direct reduced iron plant [27]. Additionally, in September 2023, Vale and Stegra signed an agreement to assess the feasibility of producing hot briquetted iron in Brazil, which could further integrate renewable hydrogen into the steel supply chain [27]. Such initiatives align with global efforts to decarbonize the steel industry, a sector that remains heavily dependent on fossil fuels.

Brazil is also exploring alternative uses for renewable hydrogen beyond industrial applications. Eletrobras, the country's largest electricity utility, and Suzano, a major pulp and paper producer, are investigating the production of synthetic fuels using biogenic CO_2 combined with renewable hydrogen. This approach could provide a sustainable pathway for producing carbon-neutral fuels, reducing dependence on fossil-derived hydrocarbons while leveraging Brazil's vast bioeconomy. As the country advances in green hydrogen development, these projects highlight the growing synergy between different sectors in transitioning to a low-carbon economy.

The global growth of green hydrogen production, highlighted by the fast increase in electrolyzer capacity and hydrogen production volumes, suggests that this is a key component of the future energy landscape. Brazil's existing renewable energy infrastructure positions it to capitalize on this trend. However, to fully unlock the potential of green hydrogen, substantial investments in technology, infrastructure, and regulatory frameworks are required. Brazil must focus on enhancing its electrolysis capacity, optimizing the use of renewable electricity, and ensuring that green hydrogen production is economically viable in the long term.

5. Conclusions

Brazil possesses the necessary renewable resources to establish itself as a major player in green hydrogen production. However, several economic, technological, and regulatory challenges must be overcome to enable large-scale deployment and ensure competitiveness with fossil fuel-derived hydrogen.

The cost of green hydrogen in Brazil currently ranges between USD 2.50 and 6.80 per kilogram. Although long-term cost reductions are expected through economies of scale and carbon pricing mechanisms, technological advancements in electrolyzer efficiency and energy storage remain critical to lowering costs in the short term. Studies indicate that for hydrogen production to become economically viable, electrolysis plants must operate for over 3000 hours annually, and the CAPEX must decrease below USD 650/kWe. If these conditions are met, green hydrogen could become cost-competitive with conventional hydrogen production by 2035.

Brazil's long-term strategy for green hydrogen also depends on infrastructure development. The country has secured significant international funding, including USD 135 million from the World Bank and a potential USD 1 billion investment following a MoU signed at COP 28. Additionally, USD 70 million has been allocated to the Pecém industrial and port complex for hydrogen infrastructure development, which will enhance large-scale production and export capacity. Expanding hydrogen-related infrastructure, particularly in port regions, will be essential for integrating Brazil into global hydrogen supply chains.

Regulatory barriers further complicate sector growth, as Brazil lacks a comprehensive legal framework for hydrogen production, storage, and distribution. The absence of standardized permitting processes and clear market structures creates investment uncertainty. To mitigate these issues, policies must streamline regulatory procedures and establish financial mechanisms that facilitate industry expansion.

Government incentives will be crucial in fostering green hydrogen adoption. Potential measures include tax incentives, subsidies for electrolyzer deployment, and preferential financing for hydrogen projects. Establishing a national hydrogen strategy with defined production targets and investment guidelines will be key to long-term sector development. Additionally, carbon pricing mechanisms and international partnerships could further support competitiveness and attract foreign investment.

Brazil's success in the global hydrogen economy will depend on strategic investments in technology, infrastructure, and regulatory improvements. By addressing these challenges, the country can leverage its renewable energy potential to drive economic growth, enhance energy security, and contribute to global decarbonization efforts.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare no conflicts of interest.

Author contributions

Conceptualization, methodology, writing—original draft preparation, G.H.R.d.S.; validation, formal analysis, investigation, data curation, G.H.R.d.S., A.N., N.N. and M.A.; resources, A.N.; writing—review and editing, C.D.B., N.N. and M.A.; visualization, G.H.R.d.S. and C.D.B.; supervision, A.N.; project administration, A.N., N.N. and M.H.M.; funding acquisition, A.N. and M.H.M. All authors have read and agreed to the published version of the manuscript.

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