v. 68, p. 70-90, Jul./Dec. 2026 http://doi.org/10.5380/dma.v68i.99650 e-ISSN 2176-9109

DeMA Desenvolvimento e Meio Ambiente

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Reversible hydroelectric power plants and green hydrogen as strategies to address energy intermittency in Brazil

Usinas hidrelétricas reversíveis e hidrogênio verde como estratégias para o enfrentamento da intermitência energética no Brasil

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Article received on **May 13, 2025**

Final version accepted on **November 12, 2025**

Published on **July 30, 2026**

Abstract: This article aims to present two strategic solutions for the issue of energy intermittency in Brazil: Pumped Storage Hydropower Plants (PSPs) and green hydrogen. The selection of these two instruments is based on the need to provide greater flexibility, stability, and reliability to the National Interconnected System (SIN), in a context of increasing energy demand and a growing share of intermittent renewable sources in the Brazilian electricity matrix. PSPs are presented as effective technologies for large-scale energy storage, capable of enhancing SIN's operational flexibility, although they face regulatory, environmental, and economic challenges. Green hydrogen, in turn, is highlighted as a promising solution for storing surplus energy, enabling the decarbonization of industrial and transport sectors, and contributing to the long-term stability of the power system.

Keywords: green hydrogen; renewable energy; energy security.

Resumo: Este artigo tem por objetivo apresentar duas soluções estratégicas para enfrentar o problema da intermitência energética no Brasil: as Usinas Hidrelétricas Reversíveis (UHRs) e o hidrogênio verde. A escolha desses dois instrumentos fundamenta-se na necessidade de proporcionar maior flexibilidade, estabilidade e confiabilidade ao Sistema Interligado Nacional (SIN), em um contexto de crescimento tanto da demanda energética quanto da participação de fontes renováveis intermitentes na matriz elétrica brasileira. As UHRs são apresentadas como tecnologia madura e eficaz para o armazenamento de energia em larga escala, capazes de proporcionar flexibilidade operacional ao SIN, embora enfrentem desafios regulatórios, ambientais e econômicos. Já o hidrogênio verde é destacado como uma solução promissora para armazenar energia excedente, viabilizar a descarbonização de setores industriais e de transporte, e contribuir para a estabilidade do sistema elétrico a longo prazo.

Palavras-chave: hidrogênio verde; energia renovável; segurança energética.

1. Introduction

Brazil's energy matrix has historically been characterized by a strong reliance on hydropower, which for decades has accounted for the majority of the country's electricity generation. In addition to being a renewable energy source, the abundance of water resources and the relatively low operating costs of hydroelectric plants – once the initial infrastructure investments have been made – have reinforced hydropower as a strategic choice for meeting the country's growing energy demand (Losekann & Hallack, 2018).

However, despite its advantages, heavy reliance on hydropower also exposes the Brazilian electricity system to specific vulnerabilities. Hydroelectric generation is highly sensitive to variations in hydrological conditions, which are influenced by seasonal climate patterns and, more recently, by the effects of climate change. Prolonged drought periods, such as those experienced in 2001, 2014–2015, and 2021, have significantly reduced reservoir levels, compromising generation capacity and increasing the risk of imbalances between electricity supply and demand (Silva, 2024).

In response to these limitations, the Brazilian power system has frequently relied on thermoelectric power plants, particularly during hydrological crises. By utilizing fossil fuels such as natural gas, diesel oil, and coal, thermoelectric plants provide dispatchable generation that helps ensure the continuity of electricity supply during critical periods. However, as noted by Acheampong (2018), this emergency measure entails high generation costs, places upward pressure on electricity tariffs, and contributes to increased greenhouse gas emissions, thereby conflicting with Brazil's decarbonization commitments.

In recent years, Brazil has sought to reduce this dependence by expanding the share of non-hydropower renewable energy sources in its electricity matrix, particularly solar and wind power. Nevertheless, these sources are also intermittent, and their growing participation in the national energy mix has intensified the challenges associated with maintaining the stability and reliability of electricity supply.

Although the diversification of the electricity matrix is an essential step toward the energy transition and the mitigation of greenhouse gas emissions, the intermittency inherent to non-dispatchable renewable sources introduces new operational challenges (Kousksou et al., 2014; Suberu et al., 2014). The lack of effective large-scale energy storage solutions and the limited capacity of the system to respond rapidly to fluctuations underscore the urgent need for technological alternatives capable of enabling the secure integration of these resources on a large scale.

In this context, two strategic solutions stand out: Pumped Storage Hydropower (PSH) and green hydrogen. PSH facilities, which are already well established in several international markets, provide substantial energy storage capacity and essential ancillary services to the Brazilian Interconnected System (SIN), including frequency regulation and peak demand management (EPE, 2025; Gallo et al., 2016). Green hydrogen, in turn, has emerged as a promising energy carrier for the medium and long term, offering a means of storing surplus renewable electricity while also supporting the decarbonization of industrial and transportation sectors that are difficult to electrify directly (Abdin et al., 2020; International Energy Agency [IEA], 2023).

Accordingly, this article aims to present and discuss two strategic alternatives for addressing the challenge of energy intermittency in Brazil: Pumped Storage Hydropower (PSH) and green hydrogen. Both solutions are analyzed in terms of their potential to enhance operational flexibility, system stability, and support for a sustainable energy transition, as well as the technical, regulatory, and economic challenges associated with their implementation.

To achieve this objective, the article is organized into four sections in addition to this introduction. The following section examines the imbalance between energy supply and demand in Brazil, highlighting the challenge posed by the intermittency of energy sources. The third and fourth sections present the theoretical and practical foundations of the two strategies proposed to mitigate intermittency within the Brazilian context. Finally, the concluding section summarizes the main findings and discusses their implications for the future development of Brazil's energy sector.

2. Imbalance between energy supply and demand in Brazil

The imbalance between energy supply and demand in Brazil is a structural challenge that affects multiple sectors of society. According to Moreira and Millikan (2012), this imbalance occurs when the amount of electricity generated is insufficient to meet consumption demand, potentially resulting in power outages, higher electricity tariffs, and broader economic losses.

Several factors contribute to this imbalance. One of the most significant is Brazil's historical dependence on hydropower, whose generation capacity is highly influenced by climatic conditions, particularly prolonged droughts. In such cases, the imbalance arises from a reduction in energy supply.

During periods of drought or below-average rainfall, as demonstrated by Queiroz et al. (2016), the reservoirs of hydroelectric power plants – the primary source of electricity generation in Brazil – often fall below optimal storage levels. This reduction in water availability compromises hydroelectric generation capacity, forcing the power system to rely on alternative sources to meet demand.

Under these circumstances, the dispatch of thermoelectric power plants becomes necessary. However, thermoelectric generation presents two major drawbacks: high costs and external dependence. Compared with hydropower, electricity generated from thermoelectric plants is considerably more expensive, leading to higher electricity tariffs for consumers. Furthermore, given that a large share of Brazil's thermoelectric generation relies on natural gas and that the country remains partially dependent on imported supplies of this fuel, a degree of reliance on external energy sources persists, as noted by Silva (2024). In other words, part of the country's energy demand is effectively supported by energy inputs originating from other countries, particularly Bolivia (Bertolo et al., 2022). This situation exposes the energy sector to a range of vulnerabilities, including fluctuations in international market prices, geopolitical risks, and potential impacts on domestic tariff stability.

Events such as those experienced in 2001, 2014–2015, and 2021 clearly illustrate this vulnerability. According to Borges (2021), the substantial decline in reservoir levels during these periods reduced electricity generation capacity, making supply insufficient to meet growing national demand. The most notable case occurred in 2001, when Brazil faced a severe energy crisis that led to the implementation of a nationwide electricity rationing program, affecting industrial, commercial, and residential activities. During the periods of 2014–2015 and 2021, although formal rationing measures were not required, the country experienced significant stress on the power system, resulting in increased reliance on thermoelectric generation and, consequently, higher electricity tariffs for end users.

The imbalance between energy supply and demand in Brazil may also arise from increasing demand, which reflects the country's economic and social development as well as changes in consumption patterns. Electricity consumption in Brazil has grown steadily over recent decades, driven by factors such as industrial expansion, urbanization, and the increasing use of electronic devices and appliances (Barbosa & Mattos, 2021).

Under a realistic scenario, this demand is expected to continue growing in the coming years. The Brazilian Energy Research Office (EPE), the National Electric System Operator (ONS), and the Electric Energy Trading Chamber (CCEE) project an average annual growth rate of 3.4% in electricity demand through 2028, with average consumption expected to reach 89,754 MW by the end of the forecast period. These projections take into account factors such as Gross Domestic Product (GDP) growth, labor market performance, and the maintenance of household consumption levels (EPE, 2024a).

Electricity transmission and distribution in Brazil also constitute significant bottlenecks that contribute to imbalances between supply and demand. Although some regions of the country, particularly the Southeast and Central-West, possess sufficient or even surplus generation capacity, limitations in transmission infrastructure may prevent electricity from being efficiently delivered to areas with higher consumption, such as major urban centers and industrial hubs (Piotrowski et al., 2021).

Brazil's transmission system, which consists of an extensive network of transmission lines and substations, faces challenges related to its ability to expand and modernize at a pace consistent with growing demand. The considerable distance between generation sites – often located in remote areas or in the North and Northeast regions – and the main consumption centers, concentrated in the Southeast and South, requires a robust and well-integrated infrastructure. However, in many cases, the existing network is constrained by capacity limitations or is vulnerable to failures resulting from aging equipment.

During periods of drought or peak demand, these transmission constraints can further exacerbate the imbalance between supply and demand. Even when electricity is available in certain regions, the lack of adequate transmission capacity may prevent it from reaching the urban and industrial centers where it is most needed. According to Borges (2021), this mismatch can lead to system overloads, increased operating costs, and, in more critical situations, power outages or supply interruptions, as occurred during the 2001 energy crisis.

In a context characterized by economic growth combined with prolonged drought periods, the energy crisis tends to become significantly more severe. Economic expansion inherently drives higher electricity demand as industrial, commercial, and residential sectors increase their levels of activity and consumption. At the same time, prolonged droughts, which frequently affect Brazil, substantially reduce the generation capacity of hydroelectric power plants.

This combination of factors – high demand and reduced supply – creates a structural imbalance within the electricity system, increasing the risks of power shortages, raising generation costs, and consequently exerting upward pressure on inflation. Such a scenario undermines the competitiveness of domestic industry, constrains economic growth, and adversely affects both productive activities and societal well-being.

The imbalance between energy supply and demand in Brazil is not determined solely by physical variables, such as rainfall patterns, reservoir levels, and installed generation capacity. Institutional factors also play a critical role by directly influencing the pace and coordination of expansion within the electricity sector. Among the most important of these factors are delays in planning and permitting processes, lengthy environmental licensing procedures, project-related litigation, and insufficient coordination between generation and transmission expansion.

Delays in updating expansion plans and issuing authorizations by the National Electric Energy Agency (ANEEL) may result in investments in new projects failing to keep pace with demand growth, thereby increasing the risk of electricity shortages and price increases in the short term. Likewise, environmental licensing procedures, while essential, are often lengthy and uncertain, particularly for hydroelectric projects and transmission lines crossing environmentally sensitive areas, causing significant delays in the commissioning of new infrastructure.

Project-related litigation further increases regulatory and financial uncertainty, frequently leading to construction delays and discouraging private investment. In addition, the lack of synchronization between generation and transmission expansion means that completed power plants may be unable to deliver electricity to the grid due to insufficient transmission infrastructure, resulting in losses and systemic inefficiencies.

Collectively, these institutional barriers contribute to a cycle of instability in which periods of insufficient supply alternate with phases of excess capacity, increasing overall system costs and undermining energy security. Addressing these weaknesses therefore requires stronger institutional governance, greater regulatory predictability, improved coordination among public agencies, and mechanisms aimed at reducing litigation, thereby ensuring the sustainable and balanced expansion of Brazil's electricity sector.

In recent years, Brazil has made significant efforts to diversify its electricity matrix in order to reduce its historical dependence on hydropower by increasing the share of non-hydropower renewable energy sources, particularly solar and wind power. This transition is strategic not only for enhancing energy security but also for aligning the country with global commitments to reduce carbon emissions and mitigate climate change (Silva & Silva, 2024).

However, both solar and wind power are inherently intermittent, as their generation depends on variable weather conditions, namely solar irradiance and wind intensity. Unlike hydroelectric plants, which can operate relatively continuously with the support of reservoirs, solar and wind facilities cannot guarantee stable electricity generation at all times (Costa et al., 2025). Consequently, the growing participation of these renewable sources in Brazil's electricity matrix introduces new technical and operational challenges for system management, particularly with respect to maintaining grid frequency and voltage stability, improving supply predictability, and ensuring the availability of complementary generation sources or energy storage systems.

Therefore, although the diversification of the electricity matrix through non-hydropower renewable sources represents a necessary and positive development, it also requires substantial investments in energy storage technologies, such as utility-scale battery systems, demand-side management mechanisms, and expanded transmission capacity to efficiently connect generation regions with consumption centers.

Accordingly, the Brazilian energy sector requires alternative solutions capable of enhancing operational flexibility, ensuring power system stability, and supporting the transition toward a sustainable energy matrix. The following sections therefore examine two promising approaches for mitigating the challenge of energy intermittency in Brazil: Pumped Storage Hydropower (PSH) and green hydrogen.

3. Pumped storage hydropower plants

The recent and substantial expansion of intermittent renewable energy sources, particularly solar and wind power, within Brazil's electricity matrix has intensified the need for efficient energy storage systems. The Ten-Year Energy Expansion Plan 2030 (PDE 2030) projected that distributed generation would contribute 24.5 GW to the Brazilian Interconnected Power System (SIN) by 2030. However, the National Energy Balance, base year 2023, indicates that distributed photovoltaic micro- and mini-generation (MMGD) alone already accounts for 26.36 GW of installed capacity and 29,813 GWh of electricity generation (EPE, 2024b). Furthermore, according to ONS (2025), MMGD represented 15.8% of Brazil's total installed capacity of 234,778 MW in March 2025.

Wind energy has also experienced remarkable growth, reaching 34 GW of installed capacity and generating an impressive 107.6 TWh of electricity, representing approximately 14% of Brazil's electricity matrix in 2024. The rapid expansion of non-dispatchable renewable sources between 2020 and 2025 has therefore accelerated the need for energy storage technologies capable of enhancing the operational flexibility of the SIN.

The Ten-Year Energy Expansion Plan 2034 (PDE 2034), published by the Brazilian Ministry of Mines and Energy (MME) and the Energy Research Office (EPE, 2025), projects that installed MMGD capacity could reach 58.8 GW under the reference scenario and 70.5 GW under the high-growth scenario. For wind power, installed capacity is expected to reach approximately 56 GW by 2034. Consequently, strategies and solutions for efficient energy storage, as well as mechanisms to address the intermittency of renewable generation, are essential to ensuring a resilient, reliable, and integrated energy future.

According to Santos et al. (2020), among the various available energy storage technologies, Pumped Storage Hydropower (PSH) stands out as a promising solution for the Brazilian electricity sector. The integration of PSH into Brazil's electricity matrix could help address many of these challenges; however, its implementation still faces regulatory, economic, technical, and socio-environmental barriers (EPE, 2025).

PSH technology, also referred to as pumped hydro energy storage, builds upon the well-established experience of conventional hydropower generation. The system operates by transferring water from a lower reservoir to an upper reservoir during periods of low electricity demand, utilizing surplus energy generated by other sources within the system. Subsequently, the stored water is released through hydraulic turbines to generate electricity during periods of higher demand, as described by Kousksou et al. (2014), Mahlia et al. (2014), Suberu et al. (2014), Canales (2015), and Zakeri and Syri (2015).

The operating principle of a pumped storage hydropower plant is therefore based on two reservoirs located at different elevations. Energy storage occurs during periods of abundant electricity availability – such as when wind speeds are high – by using surplus electricity to pump water from the lower reservoir to the upper reservoir, thereby storing energy in the form of gravitational potential energy. During periods of peak electricity demand, the stored water is released through turbines to generate electricity

(Kousksou et al., 2014; Mahlia et al., 2014; Suberu et al., 2014; Zakeri & Syri, 2015).

During the first three decades of the twentieth century, when electricity shortages were increasingly viewed as a constraint on the economic development of major Brazilian urban centers, substantial investments were made to expand the country's energy infrastructure, particularly hydroelectric generation. Brazil's first pumped storage hydropower plant was commissioned in the 1930s, followed by three additional facilities before 1955 through investments made by private companies and regional electricity concessionaires. As highlighted by EPE (2021a), Brazil became the first country in the world to install a reversible hydroelectric turbine.

However, beginning in the 1970s, the operation and expansion of PSH facilities slowed considerably due to changes in the regulatory framework, market structure, and transmission network configuration. As a result, these facilities eventually ceased operation in Brazil. The widespread adoption of conventional hydroelectric power plants with large storage reservoirs ensured system stability for several decades, postponing the need for dedicated energy storage technologies and delaying the development of regulatory frameworks for their integration into the electricity system (EPE, 2021a).

PSH facilities can also be considered a form of flexible generation due to their rapid response capabilities, enabling them to support grid frequency regulation and provide reserve capacity services (Gallo et al., 2016; Kousksou et al., 2014). Among the energy storage technologies currently available or under development worldwide, pumped storage hydropower occupies a prominent position owing to its technical and economic competitiveness. According to Kong et al. (2017), PSH offers the lowest investment cost per unit of installed capacity, the longest operational lifetime, superior reliability, and the highest level of technological maturity among large-scale energy storage solutions.

China currently possesses the world's largest installed hydropower capacity and leads globally in both conventional hydropower and pumped storage hydropower deployment. Japan ranks second worldwide in installed pumped storage capacity, according to the International Hydropower Association (2023).

The energy storage capacity of pumped storage hydropower (PSH) plants depends on the elevation difference between the upper and lower reservoirs, together with the storage volume of the reservoirs (Gallo et al., 2016; Kousksou et al., 2014; Mahlia et al., 2014; Suberu et al., 2014; Zakeri & Syri, 2015). On the other hand, PSH systems exhibit relatively low volumetric energy density (Wh/m^3), meaning that the amount of energy stored per cubic meter of water is comparatively small when measured against technologies such as electrochemical batteries, which can store substantially more energy per unit volume. Consequently, PSH facilities require either large storage reservoirs or significant elevation differences between reservoirs, limiting their deployment to sites with highly specific geographical characteristics.

Furthermore, the lengthy construction period – typically around ten years – along with high capital investment requirements and environmental concerns, particularly those associated with the flooding of large areas for reservoir construction, constitute significant barriers to the implementation of pumped storage hydropower projects (Gallo et al., 2016; Kousksou et al., 2014; Suberu et al., 2014; Zakeri & Syri, 2015).

In the current Brazilian context, PSH projects face challenges similar to those encountered by conventional hydropower plants, including technical, socio-environmental, regulatory, and financial constraints. Nevertheless, the pace of interest in and evaluation of this technology has accelerated considerably compared with previous decades, driven primarily by ongoing transformations in Brazil's energy and electricity matrices and by the growing need to meet new operational requirements of the Brazilian Interconnected System (SIN), particularly those related to flexibility and capacity adequacy.

According to EPE (2021b), PSH could serve as an important energy vector in Brazil, capable of supplying peak-load demand within the SIN while providing a high degree of flexibility to support the expansion of renewable energy sources. In addition to enhancing reliability, stability, and energy security, PSH facilities can contribute to primary and secondary frequency control, as well as provide a range of ancillary services, including spinning reserve capacity, fast-ramping response, and black-start capability. These functions play a critical role in improving the operational flexibility and stability of the interconnected power system.

In 2019, preliminary inventory studies and assessments of pumped storage hydropower potential were conducted in the state of Rio de Janeiro, enabling the identification and evaluation of prospective project sites. Through research and development partnerships with the National Electric Energy Agency (ANEEL), the Electricity Sector Studies Group (GESEL) developed analytical tools capable of assessing PSH potential across the entire country while incorporating economic feasibility considerations into the evaluation process.

Additionally, grid connection represents a critical factor in the feasibility of pumped storage hydropower (PSH) projects. Depending on the location of the facility and the available transmission capacity, the construction of new transmission lines or the expansion of existing substations may be required to ensure the proper integration of the plant into the interconnected power system. In this regard, the integrated planning of generation and transmission systems, as well as the possibility of sharing infrastructure with other generation sources, is of strategic importance for optimizing and rationalizing the associated investment costs.

According to EPE (2025), the main factors influencing the costs of pumped storage hydropower projects include installed capacity (MW), the planned duration of operation (hours), tunnel length, hydraulic head (L/H), the use of existing reservoirs or the size of newly constructed reservoirs, and the type of turbine operation adopted, whether fixed-speed or variable-speed[1]. These characteristics directly affect both the technical performance and the economic viability of PSH developments.

Socio-environmental challenges also constitute a significant consideration, as environmental licensing procedures are required for project implementation. According to EPE (2025), closed-loop PSH systems – characterized by the construction of both reservoirs outside natural watercourses – as well as projects that utilize pre-existing reservoirs, represent alternatives with strong technical and operational feasibility. Because these configurations avoid direct interference with natural river systems and require fewer structural interventions in the physical environment, they generally face less complex environmental licensing procedures and significantly lower socio-environmental impacts, thereby facilitating public acceptance and accelerating project implementation.

A comprehensive understanding of the various approaches adopted internationally for the development of pumped storage hydropower, including regulatory frameworks, market arrangements, procurement mechanisms, and remuneration models, provides valuable insights for addressing the challenges associated with the deployment of this technology in Brazil. As highlighted by recent studies, comparative analyses of international experiences can offer important lessons for the design of public policies and strategies aimed at integrating PSH into the Brazilian electricity system (Souza & Gonçalves, 2022).

4. Green hydrogen

Mitigating global warming urgently requires a substantial reduction in greenhouse gas emissions, particularly carbon dioxide (CO_2). In this context, replacing fossil fuels with renewable energy sources has become essential. Among the alternatives available to support the transition toward a low-carbon economy, green hydrogen stands out as a promising solution. Its application in industrial processes and as an alternative fuel offers significant potential for decarbonizing the energy sector, as argued by Bezerra (2021).

1 In pumped storage hydropower turbines, the type of rotational speed refers to the method used to control the speed of the turbine-generator unit. In fixed-speed machines, the rotational speed remains constant and is determined by the frequency of the electrical grid, which simplifies system control but limits operational flexibility. Variable-speed machines, by contrast, employ power electronic frequency converters that allow the rotational speed to be adjusted according to hydraulic and electrical conditions. This capability enhances energy efficiency and improves performance in frequency regulation, power balancing, and other ancillary grid services.

Obtaining hydrogen in its pure form requires separating hydrogen molecules from other components present in chemical compounds or mixtures. The resulting hydrogen can be classified into different categories, commonly identified by color codes according to the technological pathway used in its production (Sadik-Zada, 2021). According to Veiga (2022), although there is no universally accepted classification system, different colors are generally used to indicate the level of CO_2 emissions associated with the production process, with darker colors typically representing greater environmental impacts.

Grey hydrogen, for example, is produced through steam methane reforming and generates substantial CO_2 emissions. Blue hydrogen relies on the same production process but incorporates carbon capture and storage technologies to reduce emissions. Pink hydrogen is produced through electrolysis powered by nuclear energy. Green hydrogen, widely regarded as the most sustainable form of hydrogen, is generated through water electrolysis using electricity derived from renewable energy sources, such as solar and wind power[2].

According to Abdin et al. (2020), the use of hydrogen as an energy carrier for storing electricity generated from renewable sources, such as wind and solar power, together with its multiple transportation options over long distances, provides significant flexibility between energy supply and demand. Hydrogen can be transported and stored in various forms, including compressed hydrogen, liquefied hydrogen, metal hydrides (solid-state storage), Liquid Organic Hydrogen Carriers (LOHCs), and ammonia (NH_3). These characteristics enable greater dynamism within the energy system and enhance its operational flexibility. Notably, green hydrogen accounts for approximately 70% of the low-carbon hydrogen production capacity represented by projects announced worldwide, according to the International Energy Agency (IEA, 2023a).

Kovač et al. (2021) estimate that green hydrogen could represent approximately one-quarter of the global energy market by 2050, positioning it as a strategic component in the transition toward sustainable energy systems. Recognized as a clean energy carrier, green hydrogen is distinguished by its low environmental impact and is widely regarded as a promising solution for mitigating climate change. In this context, its application emerges as a viable long-term alternative for the Brazilian Electricity System (SEB), helping address challenges related to energy intermittency and the reliability of electricity supply.

Brazil possesses substantial potential for electricity generation from renewable sources, particularly hydropower, solar energy, and wind power, owing to its favorable climatic and geographic conditions. However, these energy sources are inherently intermittent, meaning that electricity generation fluctuates according to the availability of rainfall, solar radiation, and wind resources, which may compromise the stability and reliability of the electricity

2 Which can also be achieved through pumped storage hydropower (PSH), highlighting the interaction between the two alternatives proposed in this study.

system. Furthermore, although thermoelectric power plants play a strategic role in ensuring energy security, as previously discussed, their operation is associated with significant emissions of carbon dioxide (CO_2) and other atmospheric pollutants, making it more difficult for the country to achieve its environmental and decarbonization objectives.

Within this context, green hydrogen emerges as a strategic alternative by enabling the storage of surplus electricity generated from hydropower, solar, and wind sources during periods of high production. Through water electrolysis, this excess electricity can be converted into hydrogen, which may then be stored and used at a later stage when renewable energy generation declines. In addition, green hydrogen can partially or entirely replace fossil fuels currently used in thermoelectric generation. This capacity for energy storage and subsequent utilization makes green hydrogen a key element in enhancing the flexibility of Brazil's energy system, strengthening energy security, facilitating the integration of intermittent renewable resources, and supporting the diversification of the country's electricity matrix. Consequently, it contributes to reducing greenhouse gas emissions and advancing a sustainable energy transition.

Given its natural advantages and the high share of renewable resources in its electricity matrix, Brazil is well positioned to become one of the world's leading producers of green hydrogen. The Ten-Year Energy Expansion Plan 2034 (PDE 2034) is the first national planning document to incorporate an electricity demand trajectory that explicitly considers the expansion of green hydrogen production within the country (MME & EPE, 2025).

Interest in the application of green hydrogen as an energy vector for decarbonization has been growing across several sectors of the economy, including agriculture, mining, transportation, steel production, and energy storage for electricity generated from intermittent renewable sources (Gesellschaft für Internationale Zusammenarbeit, 2021).

In the steel industry, hydrogen can replace coal in the direct reduction of iron ore, thereby eliminating CO_2 emissions from the process (IEA, 2022). In the transport sector, particularly in heavy-duty modes such as trucks, trains, and ships, hydrogen represents a viable alternative to fossil fuels due to its high energy density (International Renewable Energy Agency [IRENA], 2020). These applications support the energy transition and reduce the carbon footprint of sectors that are difficult to electrify directly. Accordingly, the IEA (2023b) projects that domestic hydrogen demand in Brazil will increase by 57% in 2030 compared to 2022 under the Stated Policies Scenario, and by 94% under the Announced Pledges Scenario.

However, similarly to data centers, the adoption of green hydrogen as a solution to electricity supply intermittency is associated with uncertainties and challenges inherent to the long-term horizon. In particular, water electrolysis plants require large amounts of electricity, which may lead to a substantial increase in system load if deployed at scale, as projected by the Ministry of Mines and Energy (MME) and the Energy Research Office (EPE, 2025).

In addition, although low-emission hydrogen has significant potential to contribute to the decarbonization of hard-to-abate sectors – particularly energy-intensive industrial segments – the development of this value chain still faces important barriers. These include high production costs and insufficient infrastructure for storage and distribution. Such limitations require substantial technological advances and structural investments to enable large-scale integration into energy and industrial systems.

Moreover, unlike renewable generation plants, which are geographically more distributed and individually lower in capacity, hydrogen projects tend to be concentrated, with high power demand and located at specific points in the electricity grid. This configuration also imposes significant challenges for transmission planning, requiring targeted grid reinforcements and expansions. Nevertheless, there is a growing trend toward the development of large-scale green hydrogen projects, with capacities expected to reach hundreds of megawatts in the coming years and exceed 1 GW by 2030. According to the IEA (2023), more than 75% of the globally announced capacity for this period is concentrated in projects of this magnitude.

The high electricity demand associated with hydrogen projects imposes significant challenges for transmission planning, as their implementation will require substantial investments in grid reinforcements and expansions, often with customized solutions tailored to specific regions of the power system. Conversely, the non-realization of such projects may result in the underutilization of previously planned transmission assets. In this context, prospective studies have been increasingly used as a strategic tool to anticipate future scenarios and mitigate uncertainties related to the feasibility and deployment of large-scale hydrogen infrastructure.

According to the Ministry of Mines and Energy (MME) and the Energy Research Office (EPE, 2025), the risk of transmission asset underutilization in renewable generation projects is mitigated by the large number of developments, which are generally of moderate scale and geographically dispersed. This diversity allows the non-realization of certain projects to be offset by others within the same region, thereby reducing planning uncertainties. In contrast, the emerging hydrogen value chain presents significantly different characteristics, including an early stage of technological and market maturity at the global level, large-scale project design, geographic concentration, and a still limited number of active players.

In addition, significant financial barriers persist, particularly regarding the limited availability of long-term financing instruments dedicated to green hydrogen projects. The capital-intensive nature of these investments, combined with the still incipient maturity of the value chain and prevailing regulatory uncertainties, hinders the mobilization of private capital at a scale compatible with the sector's required development. Consequently, the absence of dedicated credit lines, appropriate guarantees, and targeted economic incentives compromises the financial viability of early-stage projects, restricting the expansion of this strategic energy alternative. Overcoming these barriers requires stronger public policy frameworks, coordinated action among financial institutions, and the development of innovative sustainable financing models.

With regard to human capital, Brazil has made notable progress, particularly through initiatives in states such as Ceará, where investments in education and technical training have contributed to workforce qualification, according to Benvindo and Moreira (2025). On the other hand, structural challenges remain in terms of infrastructure and innovation, requiring increased investment in research and development aimed at reducing external technological dependence and fostering domestic solutions.

The shortage of highly qualified professionals in fields such as process engineering, materials science, and energy technologies limits the country's capacity for innovation and for the internalization of key technologies. This gap contributes to the persistence of external technological dependence, especially in highly complex sectors such as green hydrogen, where Brazil still imports a significant share of the equipment and technical know-how required across the production chain (EPE, 2021b; IEA, 2022). Overcoming these obstacles requires expanding public and private investment in technical and higher education, as well as strengthening the integration between universities, research centers, and industry, in order to foster domestic innovation and reduce the country's technological vulnerability (Cavalcante et al., 2023; IRENA, 2020).

However, political willingness to enable the energy transition is being concretely expressed through the establishment of strategic partnerships and efforts to harmonize regulatory frameworks with international standards. Discussions on the development of low-carbon hydrogen in Brazil have advanced with the enactment of the Legal Framework for Low-Carbon Hydrogen (Lei n. 14.948, 2024). In addition, the H2 Brasil Project has produced studies and analyses aimed at structuring and developing the hydrogen market in the country, providing technical support for public policy formulation and sectoral strategies (Gomes et al., 2024).

As discussed in the Ten-Year Energy Expansion Plan 2034 (PDE 2034) (MME & EPE, 2025), Petrobras announced in 2023 the allocation of approximately US$ 11.5 billion to initiatives aimed at mitigating its environmental impacts. These resources include decarbonization measures in its operations, investments in low-carbon energy sources, hydrogen production, carbon capture, utilization and storage (CCUS) technologies, as well as low-carbon research and development projects.

Although green hydrogen is widely highlighted as a strategic energy vector and a promising option for energy storage, its use as a "battery" for the Brazilian Interconnected System (SIN) presents technical and economic limitations that must be critically assessed. The water electrolysis process used to produce hydrogen has an average efficiency of 65% to 75%, while reconversion into electricity through fuel cells rarely exceeds 50% to 60%, resulting in an overall efficiency of only 30% to 40%. This low energy efficiency implies significant losses and reduces hydrogen's competitiveness compared to other storage technologies, such as lithium-ion batteries or pumped storage hydropower plants.

In addition, the costs associated with hydrogen production, compression, transportation, and reconversion remain high, largely due to the lack of industrial scale and consolidated infrastructure in the Brazilian context. Thus, although hydrogen can play a relevant role in long-term energy storage and sector coupling, its use as a short-term solution for balancing the SIN remains economically unviable and energetically inefficient, requiring further technological and institutional advancements to become a competitive alternative in the future.

According to Castro and Delgado (2025), the growing consolidation of this new value chain will require significant investments in the construction of power generation facilities, transmission lines, and distribution networks. Indeed, early hydrogen production projects announced in Brazil confirm this global trend. According to the Ministry of Mines and Energy and the Energy Research Office (MME & EPE, 2025), although only nine projects have formally submitted grid access requests for industrial hydrogen production facilities, they collectively represent an impressive total of 35.9 GW of installed capacity projected up to 2038.

In the sensitivity analysis conducted by EPE, the most critical factors influencing the integration of green hydrogen into the national energy sector were identified. These factors directly contribute to reducing uncertainties in planning and investment scenarios, thereby supporting strategic decision-making. In the PDE 2034, simulations indicated the need to expand intermittent renewable sources (such as solar and wind) to meet the energy demand of green hydrogen projects connected to the SIN, whose operation is expected to begin in 2030. Figure 1 illustrates how the indicative expansion capacity, as determined by the system expansion optimization model, is distributed over the years.

To meet the 8.35 GW increase in electricity demand in 2034 associated with these projects, an additional supply of approximately 17.5 GW of renewable capacity was required, comprising 14.6 GW from wind power and 2.9 GW from centralized solar generation. With this additional capacity, beyond that indicated in the Reference Scenario of approximately 21.7 GW from wind and solar sources at the end of the planning horizon, the indicative expansion totals 39.1 GW for these technologies. In this context, the Ministry of Mines and Energy and the Energy Research Office (MME & EPE, 2025) highlight that the entry of a significant number of large-scale projects, such as hydrogen facilities, has a substantial impact on SIN operations and on the allocation and efficient use of system resources.

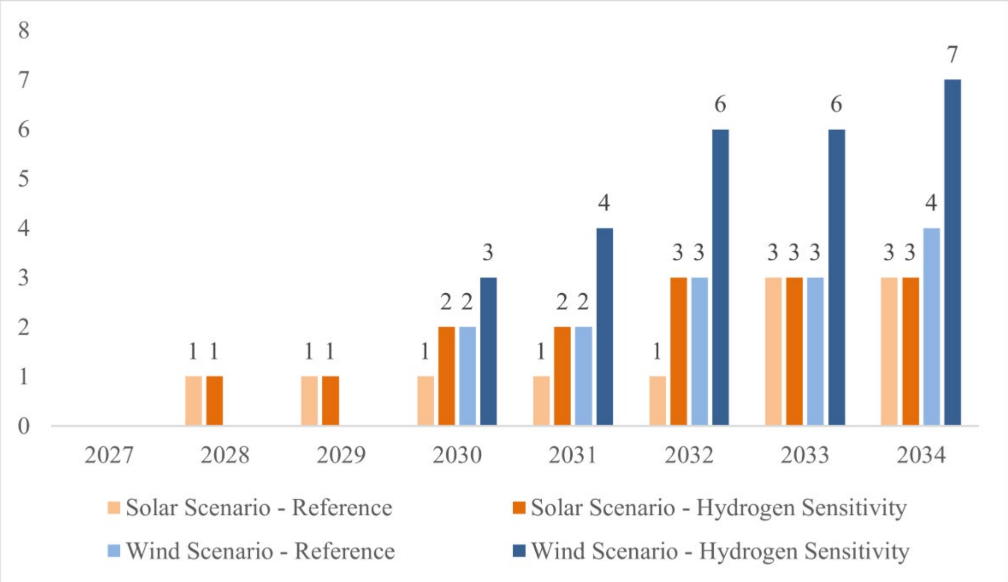

Figure 1

Sensitivity analysis of green hydrogen integration: annual expansion of wind and solar sources (GW).

SOURCE: Adapted from EPE (2025).

Thus, although the country has made progress in certain areas, structural actions are still required to ensure an effective and long-lasting energy transition, particularly to address the imbalance between supply and demand, as well as to guarantee safe and efficient processes for energy storage, transmission, and distribution.

Green hydrogen is not an immediate solution; however, it may play a fundamental long-term role in balancing energy supply and demand in Brazil. With appropriate investments and policy frameworks, it can complement the energy mix, reduce costs and emissions, and position Brazil as a global leader in the energy transition.

5. Conclusions

Energy intermittency has become one of the main challenges facing the Brazilian electricity sector, particularly due to the increasing penetration of variable renewable energy sources, such as solar and wind power, in the national electricity mix. Although these sources are essential for the energy transition and for reducing greenhouse gas emissions, their non-dispatchable nature undermines the predictability and stability of electricity supply, as their generation depends on specific climatic conditions (solar irradiation and wind intensity).

This limitation is further exacerbated by Brazil's historical reliance on hydropower generation, which is also vulnerable to climatic variability, such as prolonged drought periods. The increasing share of intermittent sources therefore heightens the need for solutions that ensure the reliability of the Brazilian Interconnected System (SIN), especially during peak demand hours or periods of low renewable generation.

In this context, the objective of this article was to present two strategic solutions – pumped storage hydropower (PSH) and green hydrogen – as technological alternatives to address the issue of energy intermittency in Brazil, analyzing their potential contributions to the flexibility, stability, and security of the National Interconnected System (SIN), as well as the technical, regulatory, and economic challenges associated with their implementation.

Pumped storage hydropower (PSH) is a well-established large-scale energy storage technology, distinguished by its ability to provide high operational flexibility to the SIN. Its operating principle is based on transferring water between two reservoirs located at different elevations, enabling energy storage during periods of low demand through pumping water to the upper reservoir, and subsequent electricity generation during periods of higher demand. Despite its strong technical potential, the expansion of PSH in Brazil is still constrained by regulatory, environmental, and economic barriers that limit its widespread adoption.

Green hydrogen is an energy carrier with significant potential for balancing electricity supply and demand by enabling the storage of surplus energy from renewable sources and its subsequent use during periods of low generation. However, it remains an emerging technology with high production and infrastructure costs, which currently limits its large-scale deployment in the short term. Therefore, green hydrogen should be understood as a promising medium- and long-term solution, particularly for the decarbonization of hard-to-electrify sectors such as industry and transport, but it is not yet a fully viable solution for addressing intermittency challenges in the Brazilian Interconnected System (SIN) within the 2025–2030 horizon.

Its large-scale deployment still faces significant obstacles, including high production costs, limited storage and distribution infrastructure, a shortage of skilled labor, and the need for specific regulatory frameworks to enable its sustainable development.

Thus, intermittency emerges as an urgent and critical challenge for ensuring a reliable, flexible, and resilient power system, driven by the increasing share of renewables in Brazil's energy and electricity matrix. Considering global technologies available for direct and indirect energy storage, pumped storage hydropower and green hydrogen stand out as highly promising options to enhance Brazil's energy security.

By presenting these two alternatives, this article contributes to the ongoing debate on technical, economic, and regulatory pathways that may ensure a secure and sustainable energy transition aligned with greenhouse gas emission reduction commitments, reinforcing the need for integrated planning and specific public policies to enable the deployment of these technologies in the country.

Despite the contributions of this study, there are broad opportunities for future research. These include analyzing the economic feasibility of implementing pumped storage hydropower plants and green hydrogen production, considering factors such as estimated costs per megawatt-hour (MWh), subsidy requirements, and competitiveness compared to other energy storage or generation technologies. Another relevant research avenue involves evaluating emerging energy storage technologies, such as lithium-ion batteries and flow batteries, which may act as alternatives or complements to PSH systems. Furthermore, studies using energy demand projections for the 2030 and 2040 horizons, available in documents from the Energy Research Office (EPE) and the National Electric System Operator (ONS), could help contextualize the need for expansion and diversification of the energy mix. Finally, the potential role of these technologies in supporting Brazil's compliance with international commitments, such as those established under the Paris Agreement, also deserves further investigation.

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