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HYDROGEN INTEGRATION IN THE BRAZILIAN ENERGY MATRIX: A COMPREHENSIVE REVIEW OF UTILIZATION TECHNOLOGIES

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ABSTRACT

Since the onset of the industrial revolution, societal progression has incessantly pursued advancements in energy generation, due to the need for amenities, which increased the final energy demand from electricity, heating and transportation. Energy consumption provides a pivotal role in technological and scientific evolution and, consequently, societal development. However, economic considerations wield considerable influence over the predominant choice of energy generation, resulting in the widespread reliance on fossil fuels since the inception of industrialization. This dependency, coupled with anthropogenic activities, has precipitated the exacerbation of climate change through greenhouse gases (GHG) emissions. Consequently, from the early 21th century onwards, the quest for alternative energy with low-GHG-emitting has intensified and the society look for more sustainable ways to energy generation. Among the current available alternatives, hydrogen has emerged as a promising alternative due to its potential utilization with low or zero GHG-emitting. This paper aims to address the gap through a comprehensive literature review focusing on hydrogen and its applications within the Brazilian context. By synthesizing existing research, it seeks to elucidate the potential applications of hydrogen within the country, thereby facilitating a clearer understanding of its feasibility as an alternative to fossil fuels. Our findings indicate that the hydrogen supply chain can be adapted to suit Brazil's unique circumstances, leveraging the nation's vast potential for different forms of hydrogen production.

1. INTRODUCTION

The widespread exploitation and increased consumption of fossil fuels throughout the past century have precipitated a cascade of environmental consequences. These include but are not limited to the exacerbation of global warming, degradation of air and water quality, amplification of extreme weather phenomena (such as alterations in precipitation patterns and the warming of oceans, which can intensify hurricanes and tropical storms), and depletion of the ozone layer, as detailed in the Environmental and Energy Study Institute (EESI) website [1]. Consequently, it has been urgent in recent years to mitigate these impacts by transitioning towards energy sources with lower carbon footprints and greater sustainability.

In Brazil, this transition is particularly pertinent given the nation's vast potential for harnessing renewable energy sources (RES). Hydrogen has emerged as a standout candidate in the decarbonization of the economy, offering a cleaner and more sustainable alternative to fossil fuels. While hydrogen itself is not a primary source of energy, its adaptability and versatility render it an attractive option across a spectrum of applications. These applications span various sectors, including transportation, electricity generation, heat production, and several industrial processes such as steel and metal manufacturing, as well as pharmaceutical and chemical production. Nevertheless, integrating hydrogen into Brazil's energy mix presents several challenges, including issues related to storage, transportation, and the development of production technologies. Hydrogen storage remains one of the major obstacles, as current storage technologies are still in development and often significantly increase the final cost of hydrogen. Transportation, closely tied to storage, also contributes to the overall expense of hydrogen. Additionally, the primary hydrogen production technologies are still in early to intermediate stages of development, which poses a challenge for hydrogen integration in Brazil.

In this context, the Brazilian government has shown a sustained interest in hydrogen production, evident through the launch of various initiatives since 1975, with the creation of the Hydrogen Laboratory (LH_2) [20]. Another projects include the implementation of the National Reference Center for Hydrogen Energy (CENEH) in 1998 [20], the PROCAC (Brazilian Hydrogen and Fuel Cell Systems Program) in 2002, later transitioning to the PROH2 (Science, Technology and Innovation Program for the Hydrogen Economy) in 2005 [2] and the National Hydrogen Program (PNH_2) in 2021 [2]. Despite that, the country figured in the top 10 of emissions per capita of CO_2 in the past two decades [35] with a emission of 2.3 billion tons of GHG in 2022, as presented in the report by D. Tsai [33], commissioned by Brazil's Climate Observatory. Notably, the energy sector ranks third among major polluters, contributing 412 million tons (Mt) of CO_2 emissions. Following closely, the transport sector emits 216.9 Mt CO_2, while the industrial sector trails with nearly 100 Mt CO_2. Based on the potential for generating hydrogen from renewable sources, known as green hydrogen [3], and the studies and programs mentioned above, Brazil could use hydrogen as an one of the alternatives to shift the paradigm and transition to a low-carbon economy.

2. LITERATURE REVIEW

This chapter offers a comprehensive literature review on studies and articles elucidating hydrogen technologies, the possible application in the Brazilian context and the challenges for hydrogen insertion in the country.

2.1 Hydrogen Production Technologies

Research into hydrogen production dates back to the early 20th century, but fossil fuel-based energy production has always held an advantage over the environmentally-friendly alternatives [5]. However, the growing transition urgency to sustainable energy sources in light of environmental concerns has sparked renewed interest in hydrogen production. Researchers are now exploring various methods to produce hydrogen, with a primary focus on reducing greenhouse gas emissions and minimizing environmental impact. Regarding, a notable advancement in hydrogen production analysis involves the implementation of a color-coded scale aimed at categorizing various production methods. While this system offers a structured way of differentiation, achieving consensus on a universally recognized standard for this scale, it remains a persistent challenge [3]. Referred to as "hydrogen rainbow", this approach utilizes distinct colors to represent different methods of hydrogen generation, as cited in Incer-Valverde and Huang articles. Nevertheless, while the color scale may vary across studies, certain similarities persist among shades, with darker hues such as grey or black, denoting more environmentally detrimental methods of hydrogen production, and progresses towards lighter shades such as green, indicative of cleaner production techniques. As of the current literature, a definitive and robust label taxonomy for hydrogen production remains to be identified.

In the research conducted by Incer-Valverde [3], ten distinct colors were identified, with the four most frequently referenced in various sources being: Grey, Green, Blue and Turquoise. All the major colors founded in the literature are depicted in the hydrogen rainbow in Tab. 1, along with another crucial parameter: the levelized cost of hydrogen (LCOH[1]), which is typically measured in $/kg of hydrogen. Nowadays, numerous studies are directed towards lowering the LCOH to enhance the commercial competitiveness of hydrogen. Consequently, each method of hydrogen production is associated with a specific levelized cost of production (LCOH$_P$) value, as detailed in Tab. 1. As cited in the introduction, the development of hydrogen technologies presents a significant challenge for hydrogen integration in Brazil. The costs associated with hydrogen production using the technologies outlined in the table already indicate that the final price of hydrogen is likely to be quite high in the short term. Moreover, production methods aligned with a low-carbon economy are often the most expensive, which could render hydrogen less competitive compared to fossil fuels in the market.

Tab. 1 – Hydrogen Production Methods. [6], [8], [10], [11], [12], [13], [15], [16], [17], [34].

Color	**Source**	**Hydrogen Production Process**	**LCOH$_P$ ($/kg)**
Black	Bituminous Coal	Gasification of anthracite or black coal. Coal gasification is a process where pulverized coal undergo partial oxidation with a gasification agent at temperatures around 1000 °C.	1.9 to 2.5
Brown	Lignite Coal or Biomass	Similar to Black hydrogen, using coal gasification. The gasification process emits substantial CO_2 and carbon monoxide, contributing to environmental concerns.	2.1 to 2.6
Grey	Natural Gas with SMR	Natural gas (NG) undergoes pre-treatment before reacting with steam in a reformer to produce carbon monoxide and hydrogen. The carbon monoxide reacts with steam in a converter tower to yield carbon dioxide and hydrogen.	0.7 to 2.3
Turquoise	NG with Methane Pyrolysis	Methane Pyrolysis is a process of thermal decomposition of methane from NG. At 1.200 ◦C without a catalyst, methane is thermally decomposed into gaseous H_2 and solid carbon.	1.6 to 3.4
Blue	NG/Biomethane with SMR and CCUS	Carbon dioxide can be captured and collected using conventional technologies like adsorption, absorption, cryogenic, and membrane systems. The collected carbon dioxide is then injected into subsurface rock formations, which can aid in hydrogen recovery.	0.99 to 2.1
Yellow	Solar with Thermochemical water-splitting	The thermochemical water-splitting process relies on the properties of specific metal oxides, which undergo reduction at high temperatures and low oxygen partial pressures, followed by re-oxidation when exposed to steam.	7.9 to 8.4
Red	Nuclear energy	Red hydrogen, a variant of pink hydrogen, is produced with thermolysis. Nuclear power is used for the high-temperature catalytic splitting of water.	2.3 to 5.9
Purple	Nuclear energy	Leverages electrolysis and thermolysis together – also referred to as thermochemical electrolysis. This innovative method harnesses nuclear energy to extract hydrogen.	2.2 to 5.7
Pink	Nuclear energy	Akin to green hydrogen, is produced through electrolysis. However, the electrolysis process for pink hydrogen is powered by nuclear energy, instead of solar or wind.	2.24 to 7.0
Orange	Electricity grid	Water Electrolysis powered by the energy mix of the country.	3.35 to 4.0
Green	RES with Water Electrolysis	Using RES to generate electricity and then converts it into hydrogen energy, through an electrolyzer.	3.2 to 7.7

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[1] The LCOH, or levelized cost of hydrogen, represents the sum of the average cost of production (LCOH$_P$), storage (LCOH$_S$) and delivery (LCOH$_D$) to a constant demand of hydrogen over the entire operational lifetime of a hydrogen supply chain system, as cited in [6].

2.2. Hydrogen Storage Technologies

Research into hydrogen storage technologies, as outlined by Amirthan et al. [7], focuses on meeting specific criteria such as high energy densities, rapid energy intake and release kinetics, operational safety, and economic feasibility. Moran and colleagues [6] delve into various storage methods, including compressed gas and liquid hydrogen storage, as well as alternative approaches like chemical compounds and solid-state storage using metal hydrides. Selection of a storage method depends on project needs, initial investment, and practical considerations. Compressed gas storage, which dominates the field, operates under high pressures of 700 to 1000 bar, with associated energy costs of approximately 10% [14]. Further details on storage methods can be found in Tab. 2.

Tab. 2 – Hydrogen storage methods. [6], [7], [9], [14], [22], [23], [24].

Method	**Key Features**	**LCOH$_D$ (\$/kgH$_2$)**
Underground Salt Caverns	Salt caverns, created within salt deposits, are utilized for storing liquid hydrocarbons and gases under high pressure (above 200 bar), offering extensive storage capacities, due to their large volumes. Rock salt's properties ensure long-term stability and gas tightness.	7 to 95
Rock Caverns	Rock caverns require competent rock with low permeability and should ideally be free of fractures and fissures. Adequate groundwater or a water curtain around the caverns is necessary for sealing and tightness.	44 to 160
Spherical Vessels	Spherical vessels are commonly used for storing natural gas (NG) at low pressures (around 20 bar), but requires a significant amount of space.	-
Underground pipes	This method is utilized for seasonal storage of NG, with a storage capacity of up to 350.000 m³ and pressures reaching 90 bar. These facilities provide protection from adverse weather conditions and the absence of above-ground structures, enabling land above to be used for other purposes.	-
Tank Type I	The storage system features an all-metal construction, designed to withstand the entire load, with a storage pressure capacity of up to 50 MPa. However, its weight is relatively high, posing potential challenges in handling and transportation.	~ 83
Tank Type II	The hybrid storage system integrates a steel vessel with glass fiber composite materials, ensuring balanced load distribution across both steel and composite components. It demonstrates remarkable pressure tolerance, capable of withstanding pressures surpassing 50 MPa. It provides a lightweight solution, between 30-40% lighter than Type I storage systems.	~ 86
Tank Type III	The storage system employs a full composite overwrap with an aluminum liner, distributing load predominantly to the composite structure while the metal liner bears minimal mechanical load. Operating at pressures around 45 MPa, it faces challenges at higher pressures like 70 MPa. It offers roughly half the weight of Type II storage systems.	~ 700
Tank Type IV	The storage system utilizes a full carbon-fiber or carbon-glass composite structure with an HDPE liner and metallic boss, capable of withstanding pressures up to 100 MPa. It offers a lightweight alternative to Type III.	~ 633
Spherical Tanks	Cryogenic storage of hydrogen as a liquid at 20 K (LH_2) is a viable method. The process of liquefying hydrogen is costly and energy-intensive. Boil-off rates present another challenge, with larger spherical tanks exhibiting lower rates compared to smaller cylindrical tanks.	-

Despite the various methods of hydrogen storage cited below, no single approach stands out as significantly better than the others in terms of efficiency and cost-effectiveness, according to the studies found in this review. This area requires more time, research, and investment for any of the existing methods, or new ones, to excel. As previously mentioned, storage remains a critical challenge in the hydrogen insertion that cannot be overlooked.

The compressed gas method results in hydrogen having an extremely low density of 0.083 kg/m³ at NTP [25], which requires a substantial amount of energy for effective management. Additionally, research highlights significant limitations in hydrogen storage capacity due to the finite volume of storage tanks. This constraint leads to higher costs, as storing larger quantities of hydrogen necessitates the use of more tanks. While storing hydrogen in its liquid form offers improved density, this method faces challenges such as higher hydrogen loss due to temperature fluctuations.

2.3. Hydrogen Transportation Technologies

The transportation of hydrogen is a crucial aspect of its integration into the energy matrix, impacting the competitiveness of the hydrogen supply chain and its adoption as an alternative energy source in the transition to a low-carbon economy. Various methods exist for hydrogen transportation, each offering unique benefits and challenges. The simplest method of transporting hydrogen is gaseous, since most hydrogen production and storage methods handle the substance in a gaseous state, as cited in the works of Muhammed [28], Zhang [29] and Ratnakar [30]. Nevertheless, the drawbacks are the high-pressure storage and transportation, which requires compression, incurring energy costs (around 10% of the gas energy content, as cited in the work by Zhang [29]) and safety concerns due to high pressure. In the works cited above, the liquid state brings some advantages, such as lower costs compared to alternative methods, practical and cost-effective solution, higher H_2 density, which makes transportation more efficient. However, the liquid form requires maintenance at extremely low temperatures (-253 ºC), evaporation during transport, limited infrastructure availability as presented in the work by Zhang [29] and Ratnakar [30]. The solid forms for transportation, such as hydrogen carriers like metal hydrides and chemical compounds like ammonia, as detailed in the articles from Zhang, Bellosta von Colbe [31] and Tong [32], are simplified method for handling and storage the hydrogen at near-ambient temperatures, despite the challenges include weight of heat exchange agents, toxicity, and limited infrastructure availability.

2.4. Hydrogen End-Use Technologies

Hydrogen utilization technologies encompass various methods for converting hydrogen into useful energy or integrating it into different applications. These technologies include fuel cells, hydrogen combustion, industrial processes and energy storage. In the content available on the Tab. 3, these technologies are presented with the main characteristics of each one. In addition, in the table is shown the probability of insertion (PI), which ranges from 0 (no chance of insertion) to 5 (great potential for insertion), based on the author analysis from the literature review and the country context. Moreover, this table also shows the GHG mitigation potential, considering the hydrogen insertion in the matrix substituting the common source of energy generation of each utilization technology. To streamline the calculation, they were performed using only green hydrogen and considering that the emissions are, based on current technology, on average, 3.0 $kgCO_2e/kgH_2$, following in the existing projects around the world, as cited in the World Economic Forum article [37]. The GHG emissions data information used in this article is available on the SEEG (Greenhouse Gas Emissions Estimates System) [36].

Beginning with the heavy-duty transport sector and light-duty transport sector CO_2 emissions in 2022 were about 115 $MtCO_2$ and 101 $MtCO_2$, respectively. In the heavy-duty transport sector, vehicles include trucks and various types of pickup trucks, totaling around 16.2 million vehicles, while the passenger transport sector comprises approximately 60.5 million automobiles, as reported by the Infrastructure Ministry [38]. According to the EPE study on freight transportation, cargo vehicles consume 30 million tons of oil equivalent (TOE) [42], while the 2023 Energy Balance Report highlights Brazil's significant gasoline consumption, totaling 24.23 Mtoe [41]. According to conversion units [39], where 1 TOE equals 345 gallons, and considering the study by D. Sáinz [40], which equates 1 kg of hydrogen to 3.8 liters of gasoline (1 gallon), and simplify calculations by assuming the main fuel to transition is from gasoline to hydrogen. Hence, the hydrogen required for heavy-duty transportation amounts to 10.35 billion kg, emitting approximately 31 $MtCO_2$, while meeting the demand for automobiles necessitates nearly 8.35 billion kg of hydrogen, emitting around 25 $MtCO_2e$. To determine the GHG Mitigation Potential of hydrogen, simply subtract the values found.

Applying the same methodology, the GHG emissions from the residential sector in 2022 amounted to 29.8 $MtCO_2e$. To determine the hydrogen needed to replace LPG for heating applications, we use the calorific power equivalency: LPG at 48 MJ/kg and hydrogen at 120 MJ/kg. According to [41], LPG consumption in 2022 totaled approximately 10.486 thousand m^3 (equivalent to 8.3 thousand tons). Therefore, the hydrogen required to meet residential demand is calculated at 3.320 tons, resulting in emissions of 9.96 $MtCO_2e$. Conversely, for the industrial sector, to replace coke-oven gas, coal coke, and natural gas in the metallurgic sector, along with fossil fuels in ammonia production for the chemical industry, we first assess the emissions. In metallurgical industrial processes, around 36.7 $MtCO_2$ emissions occurred in 2022, originating from 1.560 million m^3 of natural gas and 3.9 Mtons of coal [48]. With coal at 28.4 MJ/kg and natural gas at 37.3 MJ/m^3, approximately 14.2 Mtons of hydrogen is needed to supply the metallurgical sector, resulting in emissions of nearly 4.9 $MtCO_2e$. In the chemical sector, emissions totaled 12 $MtCO_2e$, sourced from 2.248 million m^3 of natural gas and 0.283 Mtons of coal. This equates to approximately 0.689 Mtons of hydrogen required, emitting 2.8 $MtCO_2e$.

Tab. 3 – Hydrogen Utilization Technologies. [28], [29], [30], [31], [36], [37], [41] and [42].

Technology	**Main Characteristics**	**Probability of insertion**	**Mitigation Potential**
Fuel Cells	Electrochemical devices converting chemical energy in fuel (hydrogen) to electricity without combustion.	PI = 1. Given the current context, the advancement of fuel cell technology necessitates the concurrent development of vehicles capable of utilizing this technology.	Around 84 $MtCO_2e$ could be mitigate.
Hydrogen Combustion	Direct combustion of hydrogen with oxygen to generate heat and energy	PI = 4. Hydrogen proves to be a compelling alternative to LPG, primarily due to its high calorific value compared to other substances.	Around 20 $MtCO_2e$ could be mitigate.
Industrial Processes	Use in industrial processes (steel production, ammonia synthesis); Substitutes for coke, coke-oven gas, NG, coal.	PI = 5. Hydrogen is already employed in various industrial processes, with further potential for increased utilization pending the development of the supply chain.	Around 41 $MtCO_2e$ could be mitigate.
Passenger Transport Sector	Can substitute gasoline in the vehicles using various technologies, e.g. fuel cells based on hydrogen in electric vehicles.	PI = 1. The widespread adoption of hydrogen-powered vehicles hinges on the development of suitable vehicles and an enhanced cost-benefit proposition for the general population.	Around 76 $MtCO_2e$ could be mitigate.

3. DISCUSSION AND CONCLUSION

As highlighted by Chantre et al. [21], the predominant method for global H_2 production, as in Brazil, currently relies on NG reforming without CCUS (Carbon Capture, Utilization and Storage), known as grey hydrogen. Nevertheless, in Brazil, hydrogen remains relatively minor in its contribution to the energy mix. Recognizing this gap, the country is actively investing in build its hydrogen supply chain, as outlined in the PNH_2. Brazil possesses the potential to embark on a gradual transition from its dependency on hydrogen derived from fossil fuels, initially embracing blue hydrogen and other low-GHG emission methods with the ultimate goal being to achieve widespread adoption of green hydrogen. Blue hydrogen holds particular promise for Brazil, leveraging the abundant NG resources in the southeast and northeast regions, where substantial reserves exist, estimated at approximately 424 billion m^3 of NG in 2017, according to [19], which offers ample NG and biomethane reserves conducive to blue hydrogen production, strategically positioned near areas of high industrial activity. Furthermore, despite current challenges in CCUS efficiency, incorporating these technologies could significantly reduce GHG associated with blue hydrogen production, due to the possible pivotal role of blue hydrogen in facilitating a gradual transition to a low-carbon economy. Moreover, the PNH_2 underscores the potential of harnessing hydrogen energy from biofuels like ethanol and biogas for blue hydrogen production, given the country's increasing biofuel production.

Furthermore, Brazil's significant RES potential, particularly in solar and wind resources, offers opportunities for green hydrogen production, especially in the Northeast region, as highlighted by research conducted by Santos [18]. Anticipated reductions in electrolysis-related equipment costs over the next decades, based on some studies founded for this review, further support the transition to a low-carbon economy. Leveraging these resources could enable large-scale hydrogen production, contributing to a reduction in fossil fuel dependency. Finally, orange hydrogen, powered by a mix of electricity sources from the national grid, presents another avenue for hydrogen production in Brazil, especially considering the country's reliance on RES, notably from hydroelectric plants. With slightly lower costs compared to green hydrogen, as presented in this paper, orange hydrogen can play a significant role in the early and intermediate stages of the transition to a low-carbon economy, particularly due to its potential to reduce transportation costs by being located near consumers.

In Brazil, the selection of hydrogen storage methods is influenced by factors such as demand, production scale, and application context, be it mobile or stationary. The country's vast size and distance to consumption hubs further shape these choices, alongside economic feasibility and spatial constraints. Given hydrogen's low density, effective storage is critical for both stationary and mobile uses, with the latter posing additional challenges in terms of cost-effectiveness and form factor. Compressed gas storage remains prevalent, ongoing efforts focus on refining this method to reduce costs and exploring alternative storage solutions. If Brazil moves towards a gradual transition from blue to green hydrogen, storage infrastructure must adapt accordingly. Initially, hydrogen tanks can serve as storage for initial production volumes, supporting low H_2 productions. These tanks can accommodate varying hydrogen quantities, from smaller volumes typical of orange or purple/pink hydrogen production to relatively larger quantities associated with blue hydrogen. Nevertheless, as mentioned in the article, storage remains a significant challenge for hydrogen integration. Even with the potential solutions for Brazil's scenario cited in this paragraph, further research and studies may be needed to identify the most suitable storage methods for the country's context.

Thus, leveraging Brazil's extensive road network, these tanks can facilitate hydrogen transportation via cargo vehicles. Additionally, repurposing existing underground pipelines designed for natural gas offers a feasible storage solution, potentially integrating hydrogen into the gas pipeline network at regulated levels without compromising existing infrastructure, aligning with the objectives mentioned in the PNH_2 program. As Brazil advances its hydrogen supply chain, salt and rock caverns emerge as promising storage options to accommodate high production volumes, particularly with the discovery of pre-salt reserves bolstering the viability of salt cavern storage. Therefore, the hydrogen transportation methods will be closely tied to the production and storage techniques employed. Initially, the utilization of pipeline systems, capitalizing on the existing infrastructure designed for NG transportation, or the use of tanks transported by cargo vehicles, may emerge as the most viable options. During the initial phases of the transition, gaseous transportation methods are expected to be predominant, given the nature of hydrogen production, particularly in processes like blue hydrogen where it is generated as a gas.

Vehicle transportation via tank storage is poised for widespread adoption, leveraging Brazil's extensive road network for efficient cargo movement over short to medium distances. As research advances and solid-form transportation methods become more economically viable, they could play a significant role in future hydrogen transportation, especially in industrial applications such as ammonia production or steel reduction processes, where solid hydrogen forms may be required. Additionally, the liquid form of hydrogen could gain traction, contingent upon advancements in safety measures to maintain low temperatures and minimize evaporation. Despite these challenges, the lower transportation costs associated with liquid hydrogen might enhance its commercial competitiveness, driving further adoption in the market. Finally, the utilization of hydrogen could start with metallurgic and chemical industry, residential heating and public transport vehicles, considering the technologies cited in section 2.4. Thus, with the advancement of the H_2 supply chain, others sectors will integrate hydrogen and could mitigate a high amount of GHG, around 111 million of tons of GHG, as shown in the Tab. 3.

In summary, this paper offers a comprehensive review of hydrogen technologies, elucidating their current development and potential application in Brazil's transition to a low-carbon economy. The interconnected nature of the H_2 supply chain underscores its potential advantages, as advancements in each stage facilitate overall competitiveness with other energy sources. The outlined applications for each segment of the hydrogen chain highlight Brazil's promising prospects as a major hydrogen user in its energy matrix. With the capacity for producing both blue and green hydrogen, Brazil stands poised to lead the decarbonization process through hydrogen-based initiatives. However, the country may require increased investments in research and development due to the early stages of hydrogen technologies, particularly in storage and transportation. There are numerous challenges to address in integrating hydrogen into the energy matrix, which could be explored further in additional studies.

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