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Analysis of the potential impacts of hydrogen on the energy transition in Brazil and Paraguay

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ABSTRACT

Hydrogen energy has attracted considerable attention and stimulated discussions as a favorable vector for the sustainable energy transition that is increasingly being pursued worldwide. This article presents an analysis of the possible impacts of hydrogen on the energy transition of Brazil and Paraguay. Due to the diversity of possibilities for the use of hydrogen, its inclusion as an energy vector in energy matrices is particularly relevant both in the analysis of each of the two countries individually, as well as their common points and complementarities due to their shared border and energy integration. The results describe, analyze and compare the strengths, weaknesses, opportunities and threats of each country, aiming to contribute to their national strategies. Political, economic, social, technological, environmental and legal scenarios are also considered, verifying whether they are aligned with international strategies. The objective is to evaluate whether Brazil and Paraguay are adequately prepared to participate in the "Hydrogen Economy", considering the potential impacts of including hydrogen as an energy vector in their energy matrices, seeking to contribute to increasing potential benefits and mitigating potential environmental, economic and technical problems associated with hydrogen production. It presents potential results in the areas of energy generation, as a component of industrial decarbonization and transportation, establishing relationships with theoretical references and analyzing the implications in the energy context. It explores the impacts of the hydrogen economy and its prospects, considering the challenges and opportunities for its implementation in energy matrices and presents conclusions and suggestions for the continuous improvement of the hydrogen economy in both countries.

Keywords: Hydrogen; Energy transition; Decarbonization; Brazil; Paraguay.

1. INTRODUCTION

The global energy transition has intensified interest in hydrogen as an energy vector capable of reducing environmental impacts, as highlighted by YUKESH KANNAH *et al*. [1]. The reason for this interest was described by SPILLEIR *et al*. [2], who emphasized that hydrogen is a promising alternative for reducing greenhouse gas emissions and replacing fossil fuels on a global scale. For a country to develop a hydrogen economy, it is necessary not only to have the availability of technologies, raw materials and skilled labor, but also political, institutional and regulatory planning [3].

This scenario has led several countries to develop strategies for incorporating hydrogen into their energy matrices. According to JI and WANG [4], the development of hydrogen energy is a common goal pursued by many countries to combat the current trend of global warming. In Latin America, the growing demand for renewable sources to replace fossil fuels has stimulated initiatives for hydrogen production, regulation and use. Among Latin American countries, Brazil and Paraguay have high potential for green hydrogen production, considering the availability of renewable resources and economic characteristics [5]. According to OLIVEIRA [6], Brazil already receives a large volume of investment in projects for hydrogen production. For CHANTRE *et al*. [7], from a long-term perspective, respondents highlighted decarbonization as a fundamental strategic advantage for the development of the hydrogen economy in Brazil. Since 2003, Paraguay has become more actively involved as it jointly initiated the Itaipu Binacional Hydrogen Program with Brazil, where the countries are 50% partners each, creating a shared interest in developing and participating in hydrogen programs in both countries. In this context, this article seeks to conduct a comparative analysis of hydrogen scenarios in Brazil and Paraguay using SWOT and PESTEL tools, thus evaluating the degree of preparedness of each country in the so-called "Hydrogen Economy".

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2. MATERIALS AND METHODS

The methodology adopted is exploratory and interdisciplinary, encompassing bibliographic and documentary research, analysis of national energy balances, identification of laws, policies and regulations specific to hydrogen, in addition to the application of the analytical tools SWOT and PESTEL. According to BAUMGARTEN *et al*. [8], SWOT analysis (Strength, Weakness, Opportunity, Threat) is a suitable management tool for evaluating the strengths, weaknesses, opportunities and threats of a business or project. It is a matrix that helps to identify the internal and external factors that can impact the success or failure of an undertaking. According to PUYT *et al*. [9], SWOT analysis is one of the oldest and most widely adopted strategic tools worldwide. BAUMGARTEN *et al*. [8] considers PESTEL analysis suitable for analyzing the role of hydrogen in the energy transition. This article used the factors for the PESTEL scenarios analysis of hydrogen according to MARAHATTA and SAFARI [10], and the current stage of the hydrogen economy in Brazil and Paraguay for the SWOT analysis.

In addition to the materials and methods, the author's participation since 2003 in the development of the Itaipu Binacional hydrogen programs, where Brazil and Paraguay are partners, has allowed him to follow the developments of hydrogen programs in the two countries since this period, facilitating the analysis and identification of the potential raised.

3. RESULTS

Charts 1 to 3.

The factors in Chart 3 resulted from the collection and analysis of documentary and bibliographic data. The baseline data were drawn from IPEA [32], covering strategy-specific objectives and hydrogen potential in Latin America. The analytical process followed the IEA [5] report on hydrogen in Latin America: from short-term opportunities to large-scale deployment. The data were updated based on MIGUEL [33].

4. DISCUSSION

The structuring of hydrogen in Brazil and Paraguay, following the example of the rest of Latin America in general, shows the need for efforts to achieve the necessary advances. One path that could facilitate the development of the economy in our region would be to take the example of the European Union [34–36] and create a group within Mercosur, based on the meetings of the Mercosur Scientific Diplomacy group, and develop an integrated plan, reactivating and strengthening relations through Mercosur and its organizations. For technical standards, we can use existing organizations such as COPANT (Pan American Commission for Technical Standards), AMN (Mercosur Association for Standardization) and follow the example of the DOE (Department of Energy of the United States of America) [34], which has produced unified technical standards for the production and use of hydrogen in its various segments, since in Europe there are still diversities due to the large number of countries that compose it with their specificities.

Common threats include domestic markets that are still developing for hydrogen applications, a shortage of skilled labor in all segments (which hinders the development of projects) and the lack of infrastructure necessary for the production and distribution of hydrogen. Regarding technical standards, the fact that they have not yet advanced significantly can be overcome with the adoption of international technical standards. Shared threats include the distance from large consumer markets, such as Europe, and international competition.

Finally, according to MIGUEL [33], with the detailed analysis of the survey of the diverse potential impacts that the hydrogen economy can bring to energy transition scenarios with an emphasis on sustainability for Brazil and Paraguay, we can see that it presents many opportunities in various sectors. The transportation sector stands out, as it greatly needs low-carbon fuels, especially given the current conflicts that hinder the logistics of petroleum derivatives, in the fertilizer production industry and in the decarbonization of industrial processes. In energy generation, since Brazil and Paraguay have predominantly sustainable energy matrices, this favors the production of low-carbon hydrogen, and it can also be strategic in isolated systems that need local production, although this requires fiscal incentives. In terms of threats, these mostly stem from the need for investments to implement the necessary infrastructure for this disruptive energy vector, so that Brazil and Paraguay can be competitive in the international market. This requires attracting large players with international investments to complement the investments available nationally.

5. CONCLUSION

In conclusion, the matrix analysis showed a score of 66% for Brazil and 44% for Paraguay, indicating that neither country is yet structured for a fully-fledged hydrogen-economy, although Brazil is proportionally more advanced compared to its neighbor. The detailed analysis shows the areas where each country needs to improve,

Chart 1: Matrix of the Brazilian scenario.

STRENGTHS	WEAKNESSES
– Presence of a regulatory framework through various laws, decrees, and resolutions to incentivize the hydrogen industry [11]. – Has a plan that includes a hydrogen program and a three-year work plan to guide the federal government's actions in developing the hydrogen sector [12]. – The national standardization forum is active in developing Brazilian standards for hydrogen technologies [13]. – H_2 production already exists through various renewable technological routes (ethanol, hydroelectric, solar, wind, and biomethane), in addition to initiatives for the exploration of natural hydrogen [14]. – Has developed projects for mobility such as hydrogen-powered buses and vessels, as well as Sustainable Aviation Fuel (SAF) [15]. – Has institutions and associations that bring together companies in the sector (ABH2 [16] and ABIHV [17]). – Energy matrix with natural resources from renewable energies to produce low-carbon hydrogen [13].	– The oil refining industry is a major producer of hydrogen in the country, but this production is used for internal consumption in refineries, and there is still no significantly developed and diversified domestic market for this product [6]. – The development of national technical standards still needs to evolve quantitatively [13]. – There are cost challenges in hydrogen infrastructure, re-quiring special metallurgical solutions for pipelines and tanks, which are more expensive than the infrastructure of competing energy vectors. – Technical professional training is still limited to R&D, and there is a lack of qualified human resources at both the operation and maintenance level, as well as at the engineering and technology level [18]. – Dependence on international suppliers of equipment and spare parts [19]. – The energy use of hydrogen presents technological and market challenges throughout its supply chain, which involves production, transportation, storage, and consumption [12]. – Lack of investment attraction and market generation that demands H_2. – Difficulty in the hydrogen diffusion model in the energy matrix.
OPPORTUNITIES	**THREATS**
– International scenario with a global market favorable to low-carbon hydrogen as a viable technology for the decarbonization of economies [12]. – Growing domestic demand from Petrobras for its production processes [12]. – Production of fertilizers to replace imports by the agro-industrial sector [20]. – Production of green steel for export [21]. – Replacement of fossil fuels on the road [22], river [22], and air transport sectors [15]. – Energy storage for efficiency and stability of intermittent energy source systems [23]. – Use of energy during off-peak and low-demand periods, as well as energy released from hydroelectric plants for hydrogen production [23]. – Production of electrolyzes in Brazil, given that it possesses the necessary raw materials (nickel reserves). – The natural gas resources available in the country and CO_2 capture and storage technology allow to produce blue hydrogen [24]. – The blending of hydrogen in natural gas networks can contribute to the expansion of demand and increase the efficiency of pipeline use.	– Hydrogen competes with other decarbonization solutions such as biofuels and the use of fossil fuels with Carbon Capture and Storage (CCS). – The large distances from major international consumers, such as European countries, make distance a challenge. – International competition in implementing structural actions in the value chain to produce low-carbon H_2 for export and local consumption [18]. – Regarding safety, hydrogen, being an explosive gas, increases the perception of risk for society [25]. – Low economic growth and high public debt impact the volume of public and private investments, in addition to reducing consumer demand for the product. – Difficulties in connecting and supplying energy in the short term to meet the energy-intensive demands of producing hydrogen in large volumes through electrolysis. – Difficulties for the National System Operator (ONS) in managing high load variations when the supply comes from intermittent energy sources cause a risk of instability in the interconnected electrical system [26].

such as the incomplete infrastructure for the hydrogen economy in both countries, highlighting the need for efforts to achieve the necessary advancements. The factors requiring further progress are, in this order: economic and social factors, technological factors, environmental factors, and political factors. This demonstrates a significant need for improvements in these areas. The resulting matrices for the countries' scenarios identified current strengths, weaknesses, opportunities, and threats, highlighting the relevant factors for the development

Chart 2: Matrix of the Paraguayan scenario.

STRENGTHS	WEAKNESSES
– Presence of a National Energy Policy that seeks to encourage the use of hydrogen-derived fuels [27]. – Has legislation that establishes the legal framework for the production, use, storage, commercialization, distribution, transportation and export of hydrogen, as well as the National Green Hydrogen Strategy [28]. – Is equipped with a regulatory framework for Carbon Credits aimed at trading in international markets [29]. – Legislation regulating the promotion, generation, production, development and use of electricity from non-conventional and non-hydropower renewable energy sources define green hydrogen and encourages its production through water electrolysis [30]. – Has ratified the Statute of the International Renewable Energy Agency (IRENA), which promotes the widespread and strengthened implementation and sustainable use of all forms of renewable energy favorable to the production of low-carbon hydrogen [31]. – The national standardization forum is active in developing Paraguayan standards for hydrogen technologies [31]. – Energy matrix with natural resources from renewable energies to produce low-carbon hydrogen [28].	– Several sectors that could generate a domestic hydrogen market are still absent in Paraguay, such as oil, steel or fertilizer production. – There are no government tax incentives to support the emergence of the market [28]. – Technical standards: still need to be further developed [28]. – There are technological and cost challenges in hydro-gen infrastructure, requiring special metallurgical solutions for pipelines and tanks, which are more expensive than conventional infrastructure. – Lack of human resources and insufficient training of instructors to deliver specialized workforce education programs in the country [28]. – Dependence on international suppliers of equipment and spare parts. – Lack of gas pipeline infrastructure for hydrogen transport and the absence of refueling stations for vehicles using fuel cells [28]. – Absence of specific regulations for the use, transport and storage of hydrogen, and the institutional, legal and regulatory frameworks need to provide greater stability, predictability, confidence and security for investors [28].
OPPORTUNITIES	**THREATS**
– Paraguay has a fluvial fleet for transporting its pro-duction. As it imports 100% of its fuels, this represents a major opportunity for the development of hydrogen-powered vessels [28]. – Since land transportation is also dependent on fuel imports, it would be strategic to reduce this dependence through the adoption of hydrogen-powered vehicles. – Production of fertilizers to replace imports by the agriculture sector. – Domestic SAF production could be strategic for re-fueling aircraft flying to countries that promote sustainable fuels. – Paraguay generates almost all its electricity from renewable energy, creating opportunities for low-carbon hydrogen production [28]. – As hydropower generation exceeds local demand and the surplus is exported to Brazil and Argentina, this excess could be used for hydrogen production for export [28]. – As a major agricultural producer, especially of soybeans, fertilizer production could reduce dependence on imports and stimulate hydrogen production. – In the short term, there may be concrete opportunities for hydrogen in islands and isolated systems that still exist in the country.	– Dependence on external capital for large-scale investments [28]. – Long distances to international consumer markets, making hydrogen transportation costly [28]. – Logistics: as Paraguay does not have a seaport, transport logistics are affected, which may increase costs. – Regarding safety, hydrogen, being an explosive gas, increases the perception of risk for society [25]. – Competition: international competition in the implementation of structuring actions along the value chain to produce green H_2 for export and local consumption, such as Brazil [28]. – Energy: the annual increase in energy consumption in Paraguay leads the country to use an ever-growing share of the electricity that would otherwise be exported from its binational hydropower plants, which in the long term may reduce energy surpluses available for hydrogen production.

of the hydrogen economy in Brazil and Paraguay. Thus, despite advances in public policies and the presence of many opportunities, structural weaknesses and competitive market threats, such as logistics and pricing, still exist. Common strengths include favorable public policies, regulation, legislation, and strong energy resource

Chart 3: PESTEL analysis of the matrices of Brazil and Paraguay.

POLITICAL FACTORS	BRAZIL	PARAGUAY
• Global support for hydrogen innovation	Y	Y
• Initiatives such as hydrogen hubs and hydrogen accelerators	Y	N
• Strategic policies and national roadmaps	Y	Y
ST	3	2
ECONOMIC FACTORS	**BRAZIL**	**PARAGUAY**
• Significant investments in green hydrogen	N	N
• Cost reduction through technological advances	N	N
• Diversified economic opportunities	Y	N
ST	1	0
SOCIAL FACTORS	**BRAZIL**	**PARAGUAY**
• Technology addressing consumer preferences	N	N
• Social shift toward sustainable transportation	Y	N
• Awareness campaigns shaping public perceptions	N	N
ST	1	0
TECHNOLOGICAL FACTORS	**BRAZIL**	**PARAGUAY**
• Advances in electrolysis and fuel cells	Y	N
• Ongoing research partnerships	Y	Y
• Accelerated technological progress	N	N
ST	2	1
ENVIRONMENTAL FACTORS	**BRAZIL**	**PARAGUAY**
• Green hydrogen aligned with sustainability	Y	Y
• CCUS technologies for emission mitigation	N	N
• Efficient and safe storage solutions	Y	Y
ST	2	2
LEGAL FACTORS	**BRAZIL**	**PARAGUAY**
• Supportive policies and incentives	Y	Y
• Safety standards for responsible implementation	Y	Y
• Fostering innovation through legal frameworks	Y	Y
ST	3	3
INDICES	**BRAZIL**	**PARAGUAY**
Total Score	12/18	8/18
Percentage	66%	44%

Source: IPEA, 2022 [32].
Note: Y = yes, N = no, ST = subtotal.

potential, with energy matrices predominantly based on renewable sources. Regarding weaknesses, the lack of a domestic market, the need for human resource training, especially for the operation and maintenance of equipment, and the dependence on imported equipment supplies stand out. Common opportunities include the production of fertilizers for the agribusiness sectors of both countries and sustainable fuels for all transport segments, replacing fossil fuels that emit greenhouse gases. As both countries have renewable energy in their energy matrices, they are well positioned for the production of low-carbon hydrogen. Another shared opportunity is distributed generation, since Brazil and Paraguay still have several systems isolated from their national grids.

In the case of Paraguay, all fuels for transport are imported, which means that replacing them with hydrogen would bring the additional benefit of achieving energy independence. In addition to land and air transport, Paraguay has an important river fleet for the flow of goods along the Paraguay River, which is its natural outlet to the Atlantic Ocean. Long-term policies for legal security, with incentives for the use of sustainable technologies and restrictions on polluting technologies, especially in areas with high concentrations of emissions, such as urban centers, are strategic to favor the more intensive use of non-polluting options, such as the hydrogen economy, also favoring public health, which can lead to fundamental support from the World Health Organization. Hydrogen for energy generation can be important for isolated systems such as in the northern and Chaco regions, far from the Paraguayan interconnected system.

In the case of Brazil, due to the diversity of its energy matrix and industry, the impacts of hydrogen are much broader. Like Paraguay, there are still isolated systems, especially in the north of the country, where distributed generation with hydrogen can replace fossil fuels with logistical advantages, as they can have local production. Just as in urban transport, it helps decarbonize densely populated centers with high levels of pollutants. In the naval industry, it can also supply isolated communities in the north of the country that depend on river transport due to the absence of roads, where the possibility of local production of hydrogen has a logistical advantage.

In the agro-industrial area, both Brazil and Paraguay, being highly agricultural countries, need fertilizers, and local production of hydrogenated fertilizers can reduce or even eliminate external dependence on this product. Also, in air transport, both Brazil and Paraguay have energy matrices predominantly based on renewable energies, which can facilitate the production of hydrogen for sustainable aviation fuel (SAF).

Therefore, this article can contribute to the development of public policies for the sustainable development of the hydrogen production chain and the consumer market, observing the indicators to be prioritized as indicated in the analytical matrices.

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7. DATA AVAILABILITY

The full dataset supporting the findings of this study is available upon request to the corresponding author, Marcelo Miguel. The dataset isn't publicly available because the doctoral thesis contains information that will still be published.

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