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HYDROGEN IN BRAZIL

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HYDROGEN IN BRAZIL

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CONTENT

1. INTRODUCTION

In a world rapidly transitioning towards sustainable energy solutions, hydrogen has emerged as a pivotal player in reshaping global energy landscapes. This study delves into the multifaceted realm of hydrogen within the context of Brazil, a country rich in renewable resources and poised for significant advancements in the hydrogen industry. From its historical trajectory to its current status, governmental policies, and stakeholder involvement, this study examines various dimensions of hydrogen's role in Brazil in order to identify fields of cooperation for Flemish companies, associations and research institutes.

This study initiates with a historical overview of hydrogen's presence in Brazil, tracing its evolution and significance over time. Moving on, it delves into the current status of hydrogen within the country, providing insights into ongoing developments and projects. Governmental initiatives and policies, including recent changes in leadership, are discussed to illuminate the regulatory environment shaping Brazil's hydrogen trajectory. Key stakeholders across various sectors are highlighted, underscoring their roles in driving hydrogen innovation forward.

Afterwards the study starts to focus on the potential of green hydrogen production within Brazil's unique energy landscape. It assesses the country's capability for producing green hydrogen, exploring factors like renewable energy resources that contribute to its viability. Existing green hydrogen projects showcase Brazil's commitment to sustainable energy practices and its potential to be a global contributor to the green hydrogen movement.

This study examines the key sectors where hydrogen integration holds promise in Brazil. Industries like oil, fertilizer, mining, steel and cement are scrutinized in terms of their potential for adopting hydrogen solutions. Furthermore, the transportation and energy generation sectors are explored, highlighting opportunities for hydrogen incorporation.

The global nature of the hydrogen economy is also emphasized. Strategic locations for hydrogen hubs, such as the Port of Suape, the Pecém Complex, and the Port of Açu, are discussed as potential international focal points for hydrogen activities. The study delves into international investments and partnerships, showcasing the cooperation between Brazil and countries like Germany, the Netherlands and the European Union. Lastly, the study investigates the potential for Brazil to become an exporter of green hydrogen.

2. HYDROGEN INDUSTRY IN BRAZIL

2.1 HISTORY OF HYDROGEN IN BRAZIL

During **the 1970s**, the increasing costs of fossil fuels due to oil crises led many countries to seek new energy solutions. In this context, hydrogen was identified as a potential energy carrier and an alternative resource to fossil fuels. Brazil, a country with abundant natural resources, chose to focus its investments on other resources such as hydropower, ethanol and biomass. However, **starting in the 2000s**, the country began developing initiatives associated with hydrogen and its technologies[1].

In **2002**, Brazil established the Brazilian Hydrogen and Fuel Cell Program (ProCaC), implemented by the Ministry of Science and Technology. In **2003**, it became a member of the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), created by the U.S. Department of Energy. The partnership, consisting of various countries with the aim of developing and implementing hydrogen technologies on a commercial scale, spurred new initiatives and motivated significant advancements for Brazil in the early 2000s[2]. Also in 2003, the Electric Power Research Center (CEPEL) began implementing the Fuel Cell and Hydrogen Laboratory as part of the R&D project funded by ANEEL (the federal economic regulator of the electricity sector in Brazil), titled "Development of New Technologies for Distributed Generation of Electric Energy - Low-Power Polymer Membrane Fuel Cells," carried out for the São Francisco Hydroelectric Company (CHESF). It is worth noting that the laboratory remains active and continues to undertake projects on this topic for companies within the Eletrobras group (a major power utility company).

In **2005**, the program previously known as ProCaC was renamed ProH2 (Program for Science, Technology, and Innovation for the Hydrogen Economy) with the central objective of promoting actions to drive the national development of hydrogen and fuel cell technologies[3]. With the maturity of the initiatives and partnerships established at that time, the Ministry of Mines and Energy (MME) launched the "Roadmap for the Structuring of the Hydrogen Economy in Brazil," which already presented an analysis of the entire production chain, from renewable production to end-use, particularly in the industrial sector.

However, considering that in 2005 renewable energy production technologies did not yet exhibit economic competitiveness or sufficient technological maturity, except for hydropower, the roadmap proposed a long-term vision (25 years) with the following intermediate horizons associated with competitive hydrogen production targets through different routes[4]:

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[1]. Lima, M. T. S., Souza, M. C., Flores, T. S., Cruz, N. G. S., Diamantino, H. D., Barroso, L. A., ... Macedo, M. H. M. (2014). Sobre a Situação Energética Brasileira: De 1970 a 2030. Ciência e Natura, 37(Ed. Especial UFVJM), 06-16.

[2] Lube, F. (2012). Energia do hidrogênio: mudanças paradigmáticas rumo à uma "economia verde" no Brasil (Master's thesis). Faculdade de Economia, Universidade Federal do Espírito Santo. Retrieved from http://repositorio.ufes.br/jspui/bitstream/10/5980/1/Filipe%20Lube.pdf. Accessed on July 17, 2023.

[3] CGEE – Centro de Gestão e Estudos Estratégicos. (2010). Hidrogênio energético no Brasil. Subsídios para políticas e competitividade: 2010-2025. Série Documentos Técnicos nº 07. Retrieved from https://www.cgee.org.br/documents/10195/734063/Hidrogenio_energetico_completo_22102010_9561.pdf/367532ec-43ca-4b4f-8162-acf8e5ad25dc?version=1.3. Accessed on July 17, 2021.

[4] EPE – Empresa de Pesquisa Energética. (2021). Nota Técnica – Bases para a Consolidação da Estratégia Brasileira do Hidrogênio. Retrieved from https://www.gov.br/mme/pt-br/assuntos/noticias/mme-apresenta-ao-cnpe-proposta-de-diretrizes-para-o-programa-nacional-do-hidrogenio-pnh2/HidrognioRelatriodiretrizes.pdf. Accessed on July 19, 2023.

1. By 2015: Commercial hydrogen production through natural gas reforming.
2. By 2020: Hydrogen production through water electrolysis.
3. By 2025: Hydrogen production through ethanol reforming and biomass utilization.
4. By 2030: Hydrogen production through alternative processes.

Despite hydrogen losing relevance with the discovery of the pre-salt reserves in Brazil, progress was observed in the field of Research and Development. In a survey of research projects associated with hydrogen and fuel cells in the databases of ANEEL, ANP (National Agency of Petroleum, Natural Gas, and Biofuels), and FNDCT (National Fund for Scientific and Technological Development) **from 2013 to 2018**, a total of 91 projects were identified, with funding amounting to approximately 34 million Brazilian Reais[5]. It is worth noting that, in general, the programs related to FNDCT, which focus more on basic research, are the most numerous (74 projects) and have a lower average financial contribution (an average of R$76,000). On the other hand, ANEEL and ANP projects are generally of longer duration, associated with higher levels of complexity and innovation, which is reflected in higher average investment values, ranging between R$1.5 million and R$1.9 million[6].

In the scope of nationally developed projects, the "Energy Storage" project by Companhia Energética de São Paulo (CESP) deserves mentioning. Initiated in **2017**, the project aims to produce hydrogen through an electrolyzer powered by solar and hydroelectric energy. This way, hydrogen production occurs during periods of surplus solar and/or hydroelectric energy generation, which is then stored for use during peak hours, contributing to the maintenance of the energy balance of the system[7].

The project by Furnas Centrais Elétricas S/A, which resulted in the inauguration of a green hydrogen generation plant in the area of the Itumbiara Hydroelectric Plant (Goiás) in **2021**, follows the same hydrogen production and usage model as the CESP project. Within the framework of ANEEL Public Call No. 21/2016, the R&D project aimed to seek synergies between solar and hydroelectric generation and energy storage for integration into the National Interconnected System (SIN). With an investment of approximately R$ 45 million, the project included the implementation of photovoltaic generation for hydrogen production through water electrolysis, its storage, and subsequent conversion into electrical energy through fuel cells[8].

In a scenario of great prospects, it is worth highlighting that some demonstrative projects have high potential for the maturity of this important energy vector. As an example, two projects can be mentioned. The first is the partnership between Nissan and the Genomics and Bioenergy Laboratory at The State University of Campinas (Unicamp). Since **2019** the partnership has as

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[5] EPE – Empresa de Pesquisa Energética. (2021). Nota Técnica – Bases para a Consolidação da Estratégia Brasileira do Hidrogênio. Retrieved from https://www.gov.br/mme/pt-br/assuntos/noticias/mme-apresenta-ao-cnpe-proposta-de-diretrizes-para-o-programa-nacional-do-hidrogenio-pnh2/HidrognioRelatriodiretrizes.pdf. Accessed on July 19, 2023.
[6] EPE – Empresa de Pesquisa Energética. (2021). Nota Técnica – Bases para a Consolidação da Estratégia Brasileira do Hidrogênio. Retrieved from https://www.gov.br/mme/pt-br/assuntos/noticias/mme-apresenta-ao-cnpe-proposta-de-diretrizes-para-o-programa-nacional-do-hidrogenio-pnh2/HidrognioRelatriodiretrizes.pdf. Accessed on July 19, 2023.
[7] AHK RIO – Câmara de Comércio e Indústria Brasil-Alemanha do Rio de Janeiro. (2021b, July 20). Câmara de Comércio e Indústria Brasil-Alemanha lança estudo com o mapeamento do setor brasileiro de hidrogênio. Retrieved from https://brasilien.rio.ahk.de/pt/news/news-details/camara-de-comercio-e-industria-brasil-alemanha-lanca-estudo-com-o-mapeamento-do-setor-brasileiro-de-hidrogenio
[8] CanalEnergia. (2021, July 30). Furnas começa produção de hidrogênio na UHE Itumbiara [Press release]. Agência CanalEnergia. Retrieved from https://www.canalenergia.com.br/noticias/53166122/furnas-comeca-producao-de-hidrogenio-na-uhe-itumbiara

objective the creation of a solid oxide fuel cell (SOFC) powered by ethanol, which is the first of its kind in the world for use in vehicles. The second is conducted by Hytron, with support from the State of São Paulo Research Foundation's (FAPESP) Innovative Research in Small Business Program (PIPE). The project developed a hydrogen production system through ethanol reforming, implemented in containers and with the potential to become a major facilitator for the transportation of produced hydrogen, with eventual deployment of these systems at refueling stations[9].

In the transportation sector, the "Brazilian Hydrogen Bus" project stands out, coordinated by Empresa Metropolitana de Transportes Urbanos de São Paulo (EMTU/SP) and directed by the Ministry of Mines and Energy (MME). The project involved the manufacturing, operation, and maintenance of four hydrogen fuel cell buses by a consortium of eight national and international companies: Ballard Power Systems, AES Eletropaulo, Epri, Hydrogenics, Tutto Trasporti, Nucellsys, Petrobras Distribuidora, and Marcopolo. It also included the installation of a water electrolysis hydrogen production station and refueling of the buses. As a result, Brazil became the first country in Latin America to have a fleet of buses powered by fuel cells[10]. On the 16th of December 2010, there was the start of commercial operations in the São Mateus - Jabaquara Corridor, located in the city of São Paulo.[11]

At the international level, in 2010, Brazil was recognized as a leader in Research and Development and Innovation (R&D&I) projects on hydrogen technologies in Latin America[12]. Despite this leadership position, investments in the field of hydrogen and its technologies were not sufficient to provide the expected growth for this energy vector. Between 1999 and 2007, Brazil invested around R$ 135 million in hydrogen projects, which accounted for approximately 25% of the investment made by Russia, India, and China, and 3% to 5% of the investments made by Japan, the European Union, and the United States[13].

2.2 CURRENT STATUS OF HYDROGEN IN BRAZIL

Nowadays, the production and industrial uses of hydrogen in Brazil are relatively well-established[14], with gray hydrogen consumption supplied through imports, local production by major consumers, or industrial gas companies. In Brazil, approximately 90% of hydrogen is generated through natural gas reforming. This scenario can be justified not only by the maturity of this technological route but also by the presence of various natural gas reserves in the

[9] FAPESP – Fundação de Amparo à Pesquisa do Estado de São Paulo. (2021). Retrieved from https://pesquisaparainovacao.fapesp.br/empresa_criada_no_brasil_exporta_solucoes_para_producao_de_hidrogenio/1704. Accessed on July 25, 2023.

[10] FINEP – Financiadora de Estudos e Projetos. (2015). Desafios para a implantação de ônibus a hidrogênio são debatidos na Finep. Retrieved from http://www.finep.gov.br/noticias/todas-noticias/5045-novos-desafios-para-a-implantacao-de-onibus-a-hidrogenio-sao-debatidos-na-finep#:~:text=Em%20junho%20deste%20ano%2C%20o,da%20Finep%20em%20sua%20execu%C3%A7%C3%A3o. Accessed on July 31, 2023.

[11] EMTU. (n.d.). Cronologia do projeto ônibus a hidrogênio. Retrieved July 17, 2023, from https://www.emtu.sp.gov.br/emtu/empreendimentos/projetos-de-desenvolvimento-tecnologico/onibus-a-hidrogenio/cronologia.fss

[12] CGEE – Centro de Gestão e Estudos Estratégicos. (2010). Hidrogênio energético no Brasil. Subsídios para políticas e competitividade: 2010-2025. Série Documentos Técnicos nº 07. Retrieved from https://www.cgee.org.br/documents/10195/734063/Hidrogenio_energetico_completo_22102010_9561.pdf/367532ec-43ca-4b4f-8162-acf8e5ad25dc?version=1.3. Accessed on July 20, 2023.

[13] Lube, F. (2012). Energia do hidrogênio: mudanças paradigmáticas rumo à uma "economia verde" no Brasil (Master's thesis). Faculdade de Economia, Universidade Federal do Espírito Santo. Retrieved from http://repositorio.ufes.br/jspui/bitstream/10/5980/1/Filipe%20Lube.pdf. Accessed on July 17, 2023.

[14] EPE – Empresa de Pesquisa Energética. (2021). Nota Técnica – Bases para a Consolidação da Estratégia Brasileira do Hidrogênio. Retrieved from https://www.gov.br/mme/pt-br/assuntos/noticias/mme-apresenta-ao-cnpe-proposta-de-diretrizes-para-o-programa-nacional-do-hidrogenio-pnh2/HidrognioRelatriodiretrizes.pdf. Accessed on July 19, 2023.

country. According to the Brazilian National Agency for Petroleum, Natural Gas and Biofuels (ANP), the country had 378.653 billion cubic meters of proven reserves in 2021, a growth of approximately 12% compared to 2020[15]. The country's hydrogen production is almost entirely concentrated in Petrobras, and the produced gas is not used for energy purposes but for the company's own consumption in the production of other petroleum derivatives.

Considering the abundant availability of natural gas, it is expected that blue hydrogen, which is still relatively immature in the country with only two production plants in operation, will play a significant role in the development of the hydrogen economy in Brazil. Therefore, to reduce emissions, systems such as CCS or CCUS could be used to obtain low-carbon hydrogen (blue H2). Gray H2 production emits approximately 9.5 kg of CO2/kg H2, whereas blue H2 has emissions levels 85% to 95% lower than gray H2[16].

It should be emphasized that this is still an evolving technology, with scale, cost, and efficiency constraints. The implementation of these systems will also require improvements in transportation, storage, and reuse of CO2. As of September 2021, there were approximately 135 commercial CCS units in operation or under development worldwide to capture carbon emitted in various processes[17]. Considering that the current cost of CO2 capture is around US$ 0.21/kg CO2 in a steam methane reforming (SMR) plant[18], which represents an additional 10% to the current price of gray H2, the competitiveness of blue H2 depends on a reduction in carbon capture costs.

According to the hydrogen sector mapping conducted by the Brazil-Germany Chamber of Commerce and Industry in Rio de Janeiro[19], hydrogen transportation to the end consumer is generally carried out exclusively by road due to the lack of safe liquefaction and pressurization technologies. Consequently, the current logistics are perceived as inefficient, resulting in a higher cost of transporting hydrogen itself.

2.3 GOVERNMENT INITIATIVES AND POLICIES

Despite recognizing the significant potential for hydrogen production, it can be said that Brazil has shown relatively late initiatives and technology development in the global context.

- It was only recently that the need to develop a **Brazilian strategy for hydrogen** was discussed through a technical note by the Energy Research Company (EPE) in February 2021. The document consolidated the strategy known as **"rainbow hydrogen"**, investing in various

[15] ANP – Agência Nacional do Petróleo, Gás Natural e Biocombustíveis. (2022). Boletim de Recursos e Reservas de Petróleo e Gás Natural 2021. ANP: Superintendência de Desenvolvimento e Produção. Retrieved from https://www.gov.br/anp/pt-br/centrais-de-conteudo/dados-estatisticos/reservas-nacionais-de-petroleo-e-gas-natural. Accessed on July 27, 2023.
[16] IRENA – International Renewable Energy Agency. (2019). Hydrogen: A renewable energy perspective. Retrieved from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Hydrogen_2019.pdf. Accessed on July 27, 2023.
[17] Global CCS Institute. (2022). Global status of CCS 2021. Retrieved from https://www.globalccsinstitute.com/resources/global-status-report/download/. Accessed July 30, 2023.
[18] Global CCS Institute. (2021). Global status of CCS 2020. Retrieved from https://www.globalccsinstitute.com/wp-content/uploads/2021/03/Global-Status-of-CCS-Report-English.pdf. Accessed July 30, 2023.
[19] AHK RIO – Câmara de Comércio e Indústria Brasil-Alemanha do Rio de Janeiro. (2021b, July 20). Câmara de Comércio e Indústria Brasil-Alemanha lança estudo com o mapeamento do setor brasileiro de hidrogênio. Retrieved from https://brasilien.rio.ahk.de/pt/news/news-details/camara-de-comercio-e-industria-brasil-alemanha-lanca-estudo-com-o-mapeamento-do-setor-brasileiro-de-hidrogenio

methods of hydrogen production with the goal of utilizing resource availability, demand, and localization[20].

- Additionally, in March 2021, the installation of the **Parliamentary Front for Renewable Energy** was announced. This initiative involves more than 200 parliamentarians and prioritizes energy generation through technology, hydrogen exploration, and small hydroelectric power plants[21].

- In this context, aiming to stimulate research and technological innovations, the **National Energy Policy Council (CNPE)** proposed **Resolution No. 2**, which prioritized resources for studies in seven areas, including hydrogen. The resolution, approved in March 2021, aims to align the allocation of resources for research and development with the long-term strategy of Brazil's energy sector[22].

- Subsequently, **CNPE Resolution No. 6/2021** mandated the conduction of a study to propose guidelines for the National Hydrogen Program (PNH2). In July 2021, the proposed guidelines were published, based on three pillars: public policies, technology, and the market; and six axes: strengthening technological foundations, capacity building and human resources, energy planning, legal and regulatory framework, market growth and competitiveness, and international cooperation[23].

- In 2022, **CNPE Resolution No. 6/2022** established the PNH2, aiming to strengthen the market and industry of hydrogen as an energy vector in Brazil. It also set up the program's governance under the coordination of the Ministry of Mines and Energy (MME). The principles of PNH2 include recognizing the diversity of available or potential energy sources and technological alternatives, seeking synergies and coordination with other countries, and promoting the decarbonization of the economy[24].

- With the increased focus on hydrogen's potential at the national level, EPE published **4 additional technical notes** throughout 2022. The first two discuss hydrogen production and consumption in refineries in Brazil and gray hydrogen production through steam methane reforming. Under the technical cooperation program "Brazil Energy Program" (BEP), the last two notes cover blue hydrogen production with CCS utilization and turquoise hydrogen production through natural gas pyrolysis[25].

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[20] EPE – Empresa de Pesquisa Energética. (2021). Nota Técnica – Bases para a Consolidação da Estratégia Brasileira do Hidrogênio. Retrieved from https://www.gov.br/mme/pt-br/assuntos/noticias/mme-apresenta-ao-cnpe-proposta-de-diretrizes-para-o-programa-nacional-do-hidrogenio-pnh2/HidrognioRelatriodiretrizes.pdf. Accessed on July 19, 2023.
[21] Ministério de Minas e Energia. (2021). Ministro participa de lançamento da Frente Parlamentar de Energia Renovável (FER). https://www.gov.br/mme/pt-br/assuntos/noticias/ministro-participa-de-lancamento-da-frente-parlamentar-de-energia-renovavel-fer. Accessed on August 28, 2023.
[22] MME – Ministério de Minas e Energia. (2021). H2Brasil – Expansão do Hidrogênio Verde. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. Retrieved from https://www.gov.br/mme/pt-br/assuntos/secretarias/spe/h2-brasil
[23] MME – Ministério de Minas e Energia. (2021). PNH2 – Programa Nacional do Hidrogênio – Proposta de Diretrizes. Retrieved from https://www.gov.br/mme/pt-br/assuntos/noticias/mme-apresenta-ao-cnpe-proposta-de-diretrizes-para-o-programa-nacional-do-hidrogenio-pnh2/HidrognioRelatriodiretrizes.pdf. Accessed August 6, 2023.
[24] MME – Ministério de Minas e Energia. (2022). Resolução CNPE nº 6, de 23 de junho de 2022. Institui o Programa Nacional do Hidrogênio, cria o Comitê Gestor do Programa Nacional do Hidrogênio, e dá outras providências. Retrieved from https://in.gov.br/en/web/dou/-/despacho-do-presidente-da-republica-419972141. Accessed July 28, 2023.
[25] EPE – Empresa de Pesquisa Energética. (n.d.). Publicações. Retrieved from https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/titulo/area-6/categoria-231. Accessed July 29, 2023.

- Finally, given the central role of the industrial sector in developing a hydrogen strategy, the **National Confederation of Industry**[26] published a **study titled "Sustainable Hydrogen: Perspectives and Potential for the Brazilian Industry"** in August 2022. The study examines international and national initiatives, identifies challenges and opportunities, and provides proposals and recommendations for the consolidation of a sustainable hydrogen market in Brazil.

2.3.1 The new government

In the first week of President Lula's government, State Ministers mentioned hydrogen in their inauguration speeches as a catalyst for Brazilian economic growth based on a green investment agenda and reindustrialization.

Low-carbon hydrogen aligns with the cross-cutting nature of the environmental agenda promised by the new government. The new Minister of Environment and Climate Change, Marina Silva, announced that climate issues should be present in all ministries.

- In the **Ministry of Mines and Energy** (MME), Minister Alexandre Silveira announced the **creation of the Secretariat of Planning and Energy Transition**. Its objective is to structure public policies to promote clean energy, with a particular focus on hydrogen.

- Beyond the MME, the **Ministry of Finance** is also looking at Brazil's potential to attract investments in clean energy projects. With the **establishment of a Sub-Secretariat for Sustainable Development Financing**, Minister Fernando Haddad intends to develop strategies for partnerships between Brazil and international financial institutions to implement renewable electricity and green hydrogen projects, particularly in the Northeast of Brazil.

- Green hydrogen is also a strategy of the new administration for decarbonizing the productive sectors of the Brazilian industry. Upon taking office as the head of the new **Ministry of Development, Industry, Trade, and Services** (MDIC), Vice President Geraldo Alckmin launched the **Secretariat of Green Economy, Decarbonization, and Bioindustry**.

While the speeches have yet to be translated into concrete public policies, there is a lack of a clear strategy for hydrogen in Brazil and regulatory frameworks that provide investment security and technology development in the country. Moreover, the National Hydrogen Program, launched in 2021 by the Bolsonaro government, goes against Brazil's decarbonization goals and the desires of the market by relying on multiple hydrogen production routes, including fossil sources.

Meanwhile, neighbouring countries such as Chile, Uruguay, and Colombia have chosen to follow the money and launch specific strategies for green hydrogen. Some Brazilian states have independently followed the same path, such as Ceará, Bahia, and Minas Gerais.

In an attempt to promote hydrogen, the current President of Petrobras, Jean Paul Prates, presented the Hydrogen Law proposal (PL 725/2022) when he was a senator. The text proposes

[26] CNI – Confederação Nacional da Indústria. (2022). Hidrogênio Sustentável – Perspectivas e Potencial para a Indústria Brasileira. Retrieved from https://static.portaldaindustria.com.br/portaldaindustria/noticias/media/filer_public/b4/73/b47388bd-e740-4df1-80a9-9b8ecbf9720f/estudo_hidrogenio_sustentavel.pdf. Accessed August 5, 2023.

the addition of a minimum percentage of 5% of hydrogen to the gas pipeline network by 2032, and 10% by 2050. However, the proposal has not progressed until now[27].

2.4 KEY STAKEHOLDERS IN THE HYDROGEN ECOSYSTEM

The researchers responsible for the book **"The Hydrogen Economy: Transition, Decarbonization, and Opportunities for Brazil"**[28] conducted a **survey** of stakeholders in the Brazilian ecosystem, resulting in the identification of 172 actors divided into five categories:

a) **Associations**: non-profit representative entities with activities related to the hydrogen industry and its derivatives.

b) **Research Centers**: laboratories, institutes, and research centers focused on the development of technologies, inputs, or the production of hydrogen and its derivatives.

c) **Companies**: private actors actively or potentially involved in the hydrogen production chain as producers (inputs, equipment, or hydrogen and its derivatives), consumers, or intermediaries.

d) **Government Entities**: public companies, agencies, or government bodies involved in financing, regulation, standardization, or the development of public policies associated with hydrogen and its derivatives.

e) **Universities**: Laboratories, research groups, departments, or specialized centers focusing on topics related to hydrogen and its derivatives.

2.4.1 Associations

Among the 20 associations identified, it is important to highlight the central role of the **Brazilian Hydrogen Association (ABH2)**, which is dedicated to gathering and organizing scientific research and technological development in the field of hydrogen in Brazil. The association was founded in April 2017 and has been actively involved in organizing international conferences and national congresses on hydrogen energy since 2018[29]. Due to the maturity level of the hydrogen production chain, there are still relatively few members from the industrial sector. However, recent additions to the association have included private sector companies, indicating the beginning of a dynamic value appreciation of hydrogen at the national level.

Furthermore, the role of industry segment associations such as the **Brazilian Association of Infrastructure and Basic Industries (ABDIB)**, the **Brazilian Association of Machinery and Equipment Industry (ABIMAQ)**, the **Brazilian Association of Waste-to-Energy (ABREN),** and the **Brazilian Association of Technology for Construction and Mining (SOBRATEMA)** is recognized for the development of a national production chain. These associations create a favourable

[27] epbr.com.br. (n.d.). Hidrogênio entra nos discursos, mas é a regulamentação. Retrieved from https://epbr.com.br/hidrogenio-entra-nos-discursos-mas-e-a-regulamentacao/. Accessed on July 18, 2023. 18/07/2023
[28] Castro, N.,... [et al.]. (Eds.). (2023). A economia do hidrogênio: transição, descarbonização e oportunidades para o Brasil (1st ed.). Rio de Janeiro: E-papers.
[29] ABH2 – Associação Brasileira do Hidrogênio. (n.d.). Sobre. Site oficial. Retrieved from https://abh2.org/sobre

environment for investment viability, infrastructure development, and human resource capacity building.

The **Brazil-Germany Chamber of Commerce and Industry in Rio de Janeiro** (AHK Rio) has been actively involved in attracting investments to the region, expanding bilateral trade, and strengthening business ties between German and Brazilian companies. The organization has been dedicated to promoting the use of hydrogen as a consolidated energy source in the economy, acting as pioneers in Brazil's energy transition and establishing a cross-sector network of contacts[30].

ABREN, on the other hand, focuses on coordinating projects for the implementation of energy recovery technologies from waste for hydrogen production, such as plasma gasification or fluidized bed plants. It is also a member of the Global Waste to Energy Research and Technology Council (GWC). Both institutions are committed to promoting best practices in integrated and sustainable waste management through energy recovery, known as Waste-to-Energy (WTE) or Energy from Waste (EfW)[31]. The organization has partnerships with ABH2, SOBRATEMA, and other associations.

Brand new is the **Brazilian Association of Green Hydrogen Industry (ABIHV),** established the 27th of July 2023. The organization is born with the mission to drive the production of green hydrogen and its derivatives in Brazil. The group is composed of companies considered leaders in their respective segments within the energy market in the country, such as Fortescue, Eletrobras, Comerc Energia, European Energy, Air Products, Messer, Voltalia, Yara, Siemens, and ThyssenKrupp. These companies believe in green hydrogen as a protagonist in the process of neo-industrialization and the economic and environmental sustainability of the country, as well as for the decarbonization of the global economy. One of ABIHV's missions is to create conditions for the large-scale production and commercialization of green hydrogen.

ABIHV will exclusively advocate for green hydrogen, so only companies that have GH2 as their sole production model will be represented by the organization. Its scope involves advocating for interests before the Executive and Legislative branches and Regulatory Agencies at the federal, state, and municipal levels. As such, the Association aims to foster the development of public policies focused on green hydrogen for its growth and consolidation as a strategic energy source.[32]

The **National Confederation of Industry (CNI)** is the leading representative of the Brazilian industry in advocating and promoting public policies that support entrepreneurship and industrial production. As mentioned before, CNI released a study called "Sustainable Hydrogen: Perspectives and Potential for the Brazilian Industry" in 2022. It particularly assesses the opportunities and challenges of using sustainable hydrogen as an energy vector towards a low-carbon economy. The institution's focus is on establishing regulatory frameworks that provide

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[30] AHK RIO – Câmara de Comércio e Indústria Brasil-Alemanha do Rio de Janeiro. (2023). Hidrogênio. Retrieved from https://brasilien.rio.ahk.de/

[31] ABREN – Associação Brasileira de Recuperação Energética de Resíduos.. Sobre nós. Site oficial. Retrieved from https://abren.org.br/sobre-a-abren/

[32] O Otimista. Setor de energia se une na criação de entidade para impulsionar hidrogênio verde no Brasil. Retrieved from https://ootimista.com.br/economia/setor-de-energia-se-une-na-criacao-de-entidade-para-impulsionar-hidrogenio-verde-no-brasil/ accessed on August 5, 2023.

investment security, promoting research and technology development, adopting international best practices, and conducting studies that accurately assess the sector's potential[33].

It is worth emphasizing that associations have been directly involved in mobilizing sectoral stakeholders related to hydrogen and its derivatives, as well as promoting scientific research and technological development of hydrogen in the national context. In this regard, the highlighted projects focus on the coordination among sector players, as well as fostering closer relationships and interactions with agents responsible for innovation in the hydrogen economy. ABH2 plays a direct role in organizing meetings, events, and webinars to disseminate knowledge and showcase projects developed in Brazil. Similarly, AHK has been promoting the dissemination of knowledge and innovation about hydrogen through three recent projects focused on H2V: the development of a website called "Portal de Hidrogênio Verde" (Green Hydrogen Portal) that provides information about the H2V market in Brazil, the creation of a Brazil-Germany Alliance for Green Hydrogen in 2020, and an innovation project with a focus on collaboration between Germany and Brazil[34]. On the other hand, ABREN has been developing new projects, currently in the elaboration phase, with companies and government entities aimed at white hydrogen production from solid waste.

2.4.2 Research centres

A total of 14 research centres in five states and three regions of the Federation (Northeast, Southeast, and South) have been identified. The searches conducted did not identify any actors of this nature in the North and Midwest regions, where the lowest concentrations of academic actors are also observed. Among the different actors:

- The **Leopoldo Américo Miguez de Mello Research Center (CENPES)** and **CEPEL**, located in Rio de Janeiro and affiliated with Petrobras and Eletrobras, respectively, play a central role given the position of these state-owned companies in the energy sector. CEPEL has had a Fuel Cell Laboratory (LabCelComb) since 2002, resulting from a project developed for CHESF, where it conducts Research and Development (R&D) activities in areas such as electricity generation based on fuel cells, including hydrogen production from natural gas and biomass, technical-economic evaluation of energy generation systems with fuel cells and hydrogen and studies on the development and characterization of materials and components for these systems[35].

- Another institute is the **Institute of Energy and Nuclear Research (IPEN)**, an autonomous institution linked to the Secretariat of Economic Development (SDE) of the Government of the State of São Paulo and technically and administratively managed by the National Nuclear Energy Commission (CNEN)[36]. Since 2000, its research line has focused on efficient and environmentally friendly energy systems, with a particular emphasis on the study and development of fuel cell technology.

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[33] CNI – Confederação Nacional da Indústria. (2022). Hidrogênio Sustentável – Perspectivas e Potencial para a Indústria Brasileira. Retrieved from https://static.portaldaindustria.com.br/portaldaindustria/noticias/media/filer_public/b4/73/b47388bd-e740-4df1-80a9-9b8ecbf9720f/estudo_hidrogenio_sustentavel.pdf. Accessed July 25, 2023.
[34] AHK RIO – Câmara de Comércio e Indústria Brasil-Alemanha do Rio de Janeiro. (2023). Hidrogênio. Retrieved from https://brasilien.rio.ahk.de/
[35] Eletrobras. (2013). Relatório de Gestão do Exercício de 2012. Eletrobras e Cepel. Retrieved from https://q.eletrobras.com/pt/AcessoaInformacao/Relatorio-de-Gestao-Exercicio-2012.pdf. Accessed Augst 1, 2023.
[36] IPEN – Instituto de Pesquisas Energéticas e Nucleares. (2022). Organização do IPEN. Retrieved from https://www.ipen.br/portal_por/portal/interna.php?secao_id=6. Accessed August 1, 2023.

- Also located in São Paulo, the **National Center for Energy and Materials Research (CNPEM)** combines activities carried out by UNICAMP and IPEN in the development of technologies for hydrogen generation through water electrolysis and photoelectrolysis, as well as the formulation of catalysts for subsequent use of this hydrogen[37].

- The **Research Center for Gas Innovation (RCGI)** aims to develop research and innovation for the sustainable use of natural gas, biogas, hydrogen, and the management, transportation, storage, and use of CO2 on a global scale, while also promoting knowledge dissemination and raising awareness in Brazil and other countries about the economic and energy potential of natural gas and hydrogen. Based at the University of São Paulo (USP), this center is supported by his founding sponsors, the São Paulo Research Foundation (FAPESP) and Shell, highlighting the close relationship between industry and the academic world[38].

- In the state of Paraná, the **Hydrogen Research Center (NUPHI)** at the Itaipu Technological Park (PTI) is the only research center that is part of ABH2, and it is also a member of the Paraná Network for Hydrogen Research (SIMPHI). The main objectives of the projects developed by NUPHI are to provide technological research, development, and innovation in equipment, methods, and processes, contributing to national and international partnerships for the development of the Hydrogen economy, and to master the technology of alkaline electrolyzer construction, aiming to foster the growth of small and medium-sized enterprises in Brazil. Thus, NUPHI investigates the life cycle of hydrogen, involving stages such as production, purification, compression, storage, quality control, transportation, and final use in fuel cells and other applications[39].

2.4.3 Companies

The survey of companies[40] resulted in the identification of 77 stakeholders in Brazil, with scattered activities and a wide diversity of purposes in the hydrogen value chain.

The 4 equipment producers (ThyssenKrupp and Siemens Energy supplying electrolyzer plants, and Eletrocell + Tracel with fuel cells) and 7 input producers were identified by the research, but only 64% of them have confirmed activities related to hydrogen. It is worth noting that the survey did not identify any mature national producer of electrolyzers or fuel cells on an industrial scale, despite numerous R&D efforts demonstrating the country's dependence on the importation of these technologies.

Out of the 24 hydrogen producers identified, only 80% have proven activities, primarily due to the role of companies in the electricity generation and distribution sector (9 stakeholders), as well as industrial gas supply (6 stakeholders). The oil and gas sector also plays a prominent role

[37] CNPEM – Centro Nacional de Pesquisa em Energia e Materiais. (n.d.). Conheça o CNPEM. Site institucional. Retrieved from https://cnpem.br/cnpem/
[38] FAPESP – Fundação de Amparo à Pesquisa do Estado de São Paulo. (n.d.). RCGI – Research Centre for Greenhouse Gas Innovation. Engineering Research Centers. Retrieved from https://fapesp.br/cpe/rcgi_%E2%80%93_research_centre_for_greenhouse_gas_innovation/22
[39] Parque Tecnológico Itaipu - PTI. (2023). Relatório de Resultados 2018. https://www.pti.org.br/wp-content/uploads/2023/01/PTI_Relatorio_Resultados_2018.pdf
[40] Castro, N.,... [et al.]. (Eds.). (2023). A economia do hidrogênio: transição, descarbonização e oportunidades para o Brasil (1st ed.). Rio de Janeiro: E-papers.

with 5 stakeholders, acting as both fossil-based hydrogen producers and consumers in the refining process of petroleum derivatives.

Among the 10 intermediaries, 4 have proven activities. Hytron, acquired in November 2020 by the Neuman & Esser Group from Germany, develops solutions for the Energy and Industrial Gases sectors, including studies, engineering projects, prototypes, supervision services, automation, integration and system commissioning. Three projects have already been developed with a focus on hydrogen[41]. The Port of Pecém (CE) was a pioneer in partnering with the Australian company Enegix Energy on a green hydrogen project[42]. This agreement is contributing to the development of an Alliance for Green Hydrogen in Brazil and various related projects. Similarly, the Port of Açu (RJ) presented a project for the construction of a green hydrogen plant to establish a hydrogen hub at the port[43]. The natural gas transporters TAG, NTS, and TBG own and manage pipelines, and their interest depends on a policy allowing the blending of hydrogen with natural gas, enabling the utilization of the existing logistical chain.

During the Rio Oil & Gas 2022, a renowned industry event, Prumo Logística and Neoenergia signed a memorandum of understanding to conduct studies for green hydrogen and offshore wind energy projects at Porto do Açu[44]. It is worth noting that Prumo Logística also signed a memorandum of understanding with EDF Renewables in September 2022, aiming to study the development and infrastructure of offshore wind farms in the region, as well as expressing the intention to invest in green hydrogen production in hybrid projects at Porto do Açu[45]. Previously, in May 2022, Shell Brazil and Porto do Açu had announced a memorandum of understanding for the development of a green hydrogen pilot plant, scheduled to be operational by 2025, with an initial capacity of 10 MW and the potential for expansion up to 100 MW[46]. Later in this study we will come back at the role of the ports in the Brazilian hydrogen sector.

From the end-user perspective, 47 companies were identified in the researchers' survey. Among them, **62% have proven activities,** but there is a **wide diversity of sectors involved**: oil and gas and steel industry (6 companies); natural gas distributors and mobility (4 companies); food, electricity generation, glass (2 companies); cement, fertilizers, and mining (1 company). All these sectors currently use gray hydrogen, but a transition to blue and then green hydrogen will help reduce the environmental impacts of their activities, provided there is an economic and regulatory context that makes it feasible.

Among the mentioned sectors, as previously discussed, the oil and gas industry acts as both a fossil-based hydrogen producer and consumer in the refining process of petroleum derivatives.

[41] Hytron. (2023). Projetos. Retrieved from https://www.hytron.com.br/projetos
[42] Marinho, F. (2021). Ceará receberá investimento bilionário da multinacional australiana Enegix para construção de usina de hidrogênio verde no Pecém. Click Petróleo e Gás. Retrieved from https://clickpetroleoegas.com.br/ceara-recebera-investimento-bilionario-da-multinacional-australiana-enegix-para-construcao-de-usina-de-hidrogenio-verde-no-pecem/
[43] Teixeira Jr., S. (2022). Porto do Açu quer hidrogênio verde para descarbonizar o Brasil. Capital Reset. Retrieved from https://www.capitalreset.com/hidrogenio-verde-porto-do-acu-quer-descarbonizar-o-brasil/
[44] Obriem, E. (2022). EDF Renewables e Prumo Logística firmam parceria para projetos de eólica offshore. Energia Hoje, Editora Brasil Energia. Retrieved from https://energiahoje.editorabrasilenergia.com.br/edf-renewables-e-prumo-logistica-juntas-em-eolica-offshore/
[45] Obriem, E. (2022). Prumo e Neoenergia firmam parceria em hidrogênio verde e eólica offshore. Petróleo Hoje, Editora Brasil Energia. Retrieved from https://petroleohoje.editorabrasilenergia.com.br/prumo-e-neoenergia-firmam-parceria-em-hidrogenio-verde-e-eolica-offshore/
[46] Porto do Açu. (2022). Shell Brasil e Porto do Açu anunciam projeto inédito em hidrogênio verde. Retrieved from https://portodoacu.com.br/shell-brasil-e-porto-do-acu-anunciam-projeto-inedito-em-hidrogenio-verde/

For the mobility sector, hydrogen vehicles (with pressurized tanks or onboard generation) still have a marginal share, but there are initiatives to make hydrogen usage more common. Similarly, in the aviation segment, there is significant uncertainty regarding the decarbonization trajectory.

The **remaining 38%** of stakeholders are **concentrated in fewer areas**: cement and fertilizers (7 companies); mining (2 companies); and agribusiness and mobility (1 company). Fertilizer producers are particularly interested in the potential for ammonia production through the Haber-Bosch process using blue or green hydrogen. In the case of the cement industry, the driving force behind the search for hydrogen lies in the decarbonization of resources used to meet the high energy demand of the manufacturing process. In the fourth chapter of this study, we will delve deeper into the hydrogen users' discussion.

Among the companies with a strong presence in the hydrogen economy, **Eletrocell** pioneered the manufacturing of fuel cells ranging from 1 to 50 kW and hybrid systems for various applications. Created from the R&D center at CIETEC, a technology-based business incubation hub in Brazil, Eletrocell focuses on developing innovative technologies, such as fuel cells, lithium batteries, and bipolar batteries, including their accessories and peripherals.

In 2000, Eletrocell collaborated with FAPESP and IPEN on a fuel cell project. From 2001 to 2002, they worked on an R&D project in partnership with Eletropaulo under the ANEEL program. Since 2004, they have been involved in the construction of a 50 kW fuel cell, which remains the largest one produced in the southern hemisphere to this day. Additionally, through projects with CEPEL, they developed a fuel cell with platinum and ruthenium co-catalysts in 5 kW cells. They also produced several test benches for universities in Brazil, manufacturing approximately 300 fuel cells ranging from small to larger ones with 1 kW capacity.

Similarly, **Barbosa & Barbosa Engenharia Elétrica** (BASE Energia Sustentável) is currently undertaking the two largest research and development projects for energy storage in the form of hydrogen and lithium batteries. These projects, supported by FURNAS and CESP, are approved for implementation[47] and involve hydroelectric power plants.

In the production of hydrogen from plastic conversion, commonly derived from petroleum and composed mainly of hydrogen and carbon, **Recupera** stands out for developing projects aimed at economically viable solutions to transform the issue of non-recyclable plastic waste into a green solution[48].

Among the companies with proven involvement in equipment production, **Siemens Energy** has been actively investing in green hydrogen projects and was one of the first industrial players to commit to carbon neutrality by 2030. In support of developing the H2 economy in Brazil, the company announced the construction of the Hydrogen Center for Latin America in the country. Siemens Energy's vision of positioning Brazil as the green hydrogen hub for Latin America entails building partnerships with national institutions. An example of this trend is the memorandum of

[47] H2 Verde Brasil. (2022). BASE Energia Sustentável. Banco de Empresas. Retrieved from https://www.h2verdebrasil.com.br/empresa/base-energia-sustentavel
[48] RECUPERA. (n.d.). About us. Retrieved from http://www.recupera.si/eng/

understanding signed between Siemens Energy, Eletrobras, and CEPEL in April 2021[49]. This memorandum establishes joint studies to gain comprehensive technological expertise in the H2V cycle in Brazil, from production to consumption, encompassing the dimension of a scalable pilot production plant. The results of these studies are expected to pave the way for implementing a commercially scaled hydrogen production plant with a zero-carbon footprint[50].

In alignment with the holding company, Eletronuclear has its own specific project with potential for growth, focusing on hypochlorite production, which generates H2 as a byproduct. The project produces highly pure hydrogen from seawater, with current production reaching 150 kg H2 per day (70 Nm^3/day) and the potential to produce up to 300 kg H2 per day. With the inclusion of the nuclear power plant Angra 3, hydrogen production could reach 500 kg H2 per day. Currently, the project aims to test the concept without immediate plans to develop a dedicated hydrogen production plant[51]. Simultaneously, it is recognized that hydrogen production can contribute to the long-term maintenance of nuclear power plants and enhance their social acceptance, especially when associated with carbon credits.

These companies demonstrate different scopes of operation, but their interests align and converge around the expectation that hydrogen will eventually become a key player as an energy carrier. However, in the aviation sector, hydrogen's prominence is not expected in the short term, as infrastructure changes require substantial capital investment, and the predominant decarbonization approach in the industry relies on aviation biofuels.

2.4.4 Governmental entities

Among the governmental entities, notable institutions include:

- Development banks:
    - Banco do Nordeste Brasil **(BNB)**
    - Brazilian Development Bank **(BNDES)**
- Research funding agencies:
    - National Council for Scientific and Technological Development **(CNPq)**
    - Studies and Projects Funding Agency **(FINEP)**
    - Research Development Foundation **(FUNDEP)**
- Regulatory agencies:
    - National Electric Energy Agency **(ANEEL)**
    - National Petroleum Agency **(ANP)**
    - Securities and Exchange Commission **(CVM)**

[49] Portal Solar. (n.d.). Eletrobras, Siemens Energy, e Cepel assinam memorando para estudos sobre desenvolvimento de hidrogênio verde no Brasil. Retrieved from https://www.portalsolar.com.br/noticias/tecnologia/outras-fontes/eletrobras-siemens-energy-e-cepel-assinam-memorando-para-estudos-sobre-desenvolvimento-de-hidrogenio-verde-no-brasil. Accessed on July 23, 2023.
[50] CEPEL – Centro de Pesquisas de Energia Elétrica. (2021). Eletrobras, Cepel e Siemens Energy assinam memorando sobre hidrogênio verde. Retrieved from https://www.cepel.br/2021/04/08/eletrobras-cepel-e-siemens-energy-assinam-memorando-sobre-hidrogenio-verde/
[51] Souza, D. (2021). Projeto inovador da Eletronuclear pode colocar a empresa na vanguarda da produção de hidrogênio verde no país. Petronotícias. Retrieved from https://petronoticias.com.br/projeto-inovador-da-eletronuclear-pode-colocar-a-empresa-na-vanguarda-da-producao-de-hidrogenio-verde-no-pais/

- Standardization bodies:
    - Brazilian Association of Technical Standards **(ABNT)**
    - National Institute of Metrology, Quality, and Technology **(INMETRO)**
- Policy-making participants:
    - Center for Strategic Management and Studies **(CGEE)**
    - Energy Research Company **(EPE)**

These institutions play a strategic role in ensuring the success of constructing and strengthening a competitive productive chain at the national level.

Solid research support for the development and/or adaptation of national technology constitutes an essential step in making Brazil a prominent player in the international H2 market. Worth mentioning are the research and development programs of **ANEEL** and **ANP**, which finance research projects in the electric power and oil and gas sectors. **FINEP** focuses on funding projects involving industrial and academic partners, particularly in the mobility sector.

The formulation of clear public policies regarding this energy product allows for stimulating the development of infrastructure in the medium and long term, mitigating investor risks in a still nascent national market. Additionally, the creation and/or adaptation of regulations and standards, discussed notably in the Brazilian National Standards Organization (ABNT) Special Study Committee for Hydrogen Technologies (ABNT/CEE-67), encompass technical aspects (particularly concerning quality and safety), economic aspects, and environmental aspects for production, transportation, storage, and usage. This constitutes one of the main challenges in encouraging the growth of H2 technologies in Brazil. In this regard, the 2050 National Energy Plan (PNE) and the report "Bases for the Consolidation of the Brazilian Hydrogen Strategy" represent the latest contributions from EPE in defining Brazil's short, medium, and long-term H2 strategy[52].

Finally, in a globalized world, the Brazilian Securities and Exchange Commission (**CVM**) will play an important role through the issuance of green bonds, which can boost private initiatives' financing.

The Brazilian Development Bank (**BNDES**) is responsible for directly supporting the implementation, expansion, modernization, construction, integration, and assembly of facilities and/or services for petroleum refining, biorefineries, synthetic fuel production, hydrogen, bioproducts production, and fuel storage through investments. In recent years, BNDES has been focused on promoting sustainable development initiatives and continues to announce projects in this direction. Similarly, different levels of involvement in the hydrogen value chain have been identified among government entities. BNDES, which currently invests in companies with sustainable scope, is closely monitoring the market dynamics. In July 2022, BNDES announced a program to support pilot projects for the production or use of green hydrogen.

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[52] EPE – Empresa de Pesquisa Energética. (2021). Nota Técnica – Bases para a Consolidação da Estratégia Brasileira do Hidrogênio. Retrieved from https://www.gov.br/mme/pt-br/assuntos/noticias/mme-apresenta-ao-cnpe-proposta-de-diretrizes-para-o-programa-nacional-do-hidrogenio-pnh2/HidrognioRelatriodiretrizes.pdf. Accessed on July 19, 2023

The maximum financing amount is R$ 300 million, and it will be sourced from the Climate Fund, dedicated to the renewable energy chain. According to the bank, the plan is to soon expand its financing lines to also support large-scale green hydrogen production projects for export.

In this case, the required investments solely for constructing the plants could reach tens of billions of reais. To grasp the necessary capital volume, the French Qair project in Pernambuco for example is estimated at R$ 20 billion[53]. More about this project will be discussed later in this study.

Meanwhile, INMETRO, within its scope of action, has historically played a significant role in the development of standards and guidelines for H2 and has a long track record of participation in shaping the hydrogen economy within the national context. Some examples of INMETRO participations:

- 2007-2012: Project participation. Data gathering to promote the structuring of the hydrogen economy utilization network, by MCT (Ministry of Science and Technology).
- 2007-2009: Fuel Cell Testing and Dissemination (FCTEDI), part of the FP6 Framework Project 6, under the auspices of the European Commission.
- 2007-2017: Institutional project "Implementing Metrological Standardization for Hydrogen as an Energy Source."
- 2017-present: Participation in the development of Chapter 7 of the Roadmap for Structuring the Hydrogen Economy in Brazil.
- 2018-present: Institutional project "Metrology in Energetic Hydrogen"; Participation with the Brazilian delegation of IPHE (International Partnership for Hydrogen and Fuel Cells in the Economy).

2.4.5 Universities

It is important to note that, although in a heterogeneous manner, all regions of the country have groups whose activities are oriented towards the production, transportation, storage, and use of H2. However, this distribution of academic actors, even though concentrated in 16 states (out of a total of 27, including the Federal District (DF)), demonstrates a capacity for nucleation throughout the federation. Some groups are still in their early stages and need consolidation, such as in the formation of thematic networks and/or local cooperation.

The survey on the activities[54] mainly pointed to research focused on the production and use of H2, but there were also identified working groups studying the storage and transportation of this resource. Among the analysed topics, there is a nationalization of the challenges observed in the hydrogen economy, particularly in the choice of resources used for hydrogen production (natural gas, ethanol, and water) and the development of catalysts for both electrolysis and fuel cells.

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[53] EPBR. (n.d.). BNDES lança programa para financiar projetos-pilotos de hidrogênio verde. Retrieved from https://epbr.com.br/bndes-lanca-programa-para-financiar-projetos-pilotos-de-hidrogenio-verde/. Accessed on July 20, 2023.
[54] Castro, N.,... [et al.]. (Eds.). (2023). A economia do hidrogênio: transição, descarbonização e oportunidades para o Brasil (1st ed.). Rio de Janeiro: E-papers.

Some research groups emerged with the launch of the ProCaC Program (see p 4) and, therefore, have expertise in the field of materials for fuel cells and electrolyzers, such as the **Federal University of Minas Gerais (UFMG)**, the **Federal University of Rio de Janeiro (UFRJ)**, and the **State University of Campinas (Unicamp)**. Research groups from the **Federal University of Ceará (UFC)** and **Unicamp** have research projects for hydrogen production from urban and food waste, respectively. One of the groups at the **Federal University of São Carlos (UFSCar),** as well as UFRJ, works on methane and ethanol reforming research.

In depicting the institutions and research groups involved in studies and projects on hydrogen, it is worth highlighting the **Hydrogen Laboratory (LabH2)** at the Alberto Luiz Coimbra Institute of Graduate Studies and Research in Engineering (COPPE/UFRJ), which is exclusively dedicated to hydrogen energy, developing fuel cells and heavy-duty electrically powered vehicles for 35 years. One of its most well-known projects was the production of a hybrid electric and hydrogen vehicle, with its first prototype completed in 2010 and its latest, the third one, developed and demonstrated at the Rio 2016 Olympic Games, all of them operational. Moreover, the laboratory itself was responsible for the founding of ABH2[55].

Also in Rio de Janeiro, **PUC-Rio**, through the Vehicle Engineering Laboratory of the Mechanical Engineering Department, is actively involved in the development of new fuels, with a focus on research on hydrogen as a form of energy storage and generation[56].

Another important player is the **Hydrogen Laboratory (LH2)** at Unicamp, which produces hydrogen through various processes such as hydrogen purification by PSA and TSA processes (Pressure Swing Adsorption and Temperature Swing Adsorption units), as well as applies hydrogen in distributed electricity generation projects. Notably, LH2 was involved in constructing the first hydrogen-powered fuel cell vehicle in the southern hemisphere and the first national fuel cell vehicle overall, known as the VEGA II Project[57].

On the other hand, the **Federal University of Goiás (UFG)** conducts studies on pure hydrogen to activate the electrochemical system and the system's activity for ethanol oxidation, as well as energy conversion in electrolytic cells.

UFSCar conducts fundamental research projects, focusing on variable parameters in hydrogen evolution reactions and materials for fuel cells, batteries, and electrolyzers. Additionally, the university has the Center for the Development of Functional Materials (CDMF), one of the Research, Innovation, and Dissemination Centers funded by FAPESP. CDMF studies materials capable of reducing energy consumption in the chemical process of water molecule decomposition, aiming to increase the efficiency of electrolyzers[58].

The **State University of Ceará (UECE)** has a history of involvement with various projects in hydrogen technology, mainly focused on the Northeast region. Since 2010, the university faculty

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[55] LABH2 – Laboratório de Hidrogênio da COPPE/UFRJ. (n.d.). Site Institucional. Retrieved from http://www.labh2.coppe.ufrj.br/index.php/pt/

[56] PUC-RIO. (2022). Laboratório de Engenharia Veicular da PUC-Rio. Retrieved from https://mec.puc-rio.br/?pag=laboratorios&lab=24

[57] AHK RIO – Câmara de Comércio e Indústria Brasil-Alemanha do Rio de Janeiro. (2023). Hidrogênio. Retrieved from https://brasilien.rio.ahk.de/

[58] CDMF – Centro de Desenvolvimento de Materiais Funcionais. (2022). Brasil prepara-se para iniciar produção de hidrogênio verde. Retrieved from http://cdmf.org.br/2022/04/07/brasil-prepara-se-para-iniciar-producao-de-hidrogenio-verde/

has advocated for the potential of renewable hydrogen technologies, discussing and analysing projects in the institution.

The **Federal Institute of Ceará (IFCE)**, similarly, has experience in the photocatalytic production of H2 using active catalysts under visible light and the production of drinking water through reverse osmosis operated by gears/piston systems powered by wind, solar, and/or batteries.

The **Federal University of Ceará (UFC)** is directly involved in projects associated with H2V production, utilizing bioelectrochemical technologies (microbial electrolysis cells) in conjunction with wastewater treatment, as well as glycerol production through steam reforming. Furthermore, UFC has established partnerships with Princeton and Columbia universities in the United States and the National Renewable Energy Laboratory of the US for hydrogen generation from wastewater using a microbial fuel cell, demonstrating Brazil's capacity to create international initiatives for R&D of disruptive technologies[59].

In contrast to what is observed in Ceará, the **Federal University of Rio de Janeiro (UFRJ),** through the Hydrogen Technologies Laboratory (LabTecH), specializes in grey hydrogen production. Additionally, the group works on obtaining catalyst materials for H2 production. Over time, the group has worked on gasification projects, expanding mainly into the biomass field. Currently, the group has several projects focused on glycerol-based H2 production[60].

In the context of international partnerships, the **Fuel Cells and Materials Laboratory (LaMPaC)** at the Chemistry Department of UFMG has undertaken a vast array of projects over the past decades. In 1988, the group had a partnership with the National Polytechnic Institute (INP) of Grenoble, France, and in 2004, they participated in the Bilateral Agreement Brazil-Portugal CNPq/GRICES. Since then, they have been developing numerous projects on solid oxide fuel cells both nationally and internationally (with INP in France and the Industrial University of Santander in Colombia), generating thematic networks[61].

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[59] ANDIFES – Associação Nacional dos Dirigentes das Instituições Federais de Ensino Superior. (2019). UFC – Pesquisadores geram hidrogênio a partir do esgoto. Retrieved from https://www.andifes.org.br/?p=81798
[60] LABTECH – Laboratório de Tecnologia do Hidrogênio. (2022). Site institucional. Retrieved from http://www.labtech.eq.ufrj.br/
[61] LAMPAC – Laboratório de Materiais e Pilhas a Combustível. (n.d.). Projetos e Parcerias. Retrieved from https://zeus.qui.ufmg.br/~lampac/projetos-e-parcerias/

3. GREEN HYDROGEN PRODUCTION IN BRAZIL

Due to the various initiatives of the several stakeholders, the first signs of the birth of a hydrogen economy are already seen in Brazil. The project "Green Hydrogen Hub, Pecém – Ceará" deserves a mention. It was launched by the State Government of Ceará, the Pecém Complex (CIPP S/A), the State Federation of Industries (FIEC) and the Federal University of Ceará (UFC). The project has attracted companies interested in the green hydrogen value chain, which ranges from the generation of the renewable energy to the production of green hydrogen and its byproducts, storage, distribution, domestic consumption, and export.

The Northeast Region, where Ceará state is located, has favorable characteristics for the production of green hydrogen. It has a potential for solar and (off- and onshore) wind power that enables the creation of hybrid power plants that can provide renewable energy at competitive prices and low intermittence. In addition, it is well placed to access the international market, since it is more or less 3 weeks away from the European ports.

The Southeast Region has a concentration of industrial activities such as steel mills and oil refineries. Furthermore, the Southeast also has a greater supply of natural gas, biomethane and ethanol that could be inputs to increase hydrogen production in the region.

3.1 GREEN HYDROGEN PRODUCTION POTENTIAL IN BRAZIL

We would like to emphasise that Brazil has a competitive advantage, being **one of the best-placed countries for producing green hydrogen**. Brazil's energy supply mix includes 85% of renewable sources; it is the third country in the world that generates most renewable energy. Furthermore, a significant share of the new capacity added to the system comes from solar and wind power, with increasingly attractive costs. For instance, at the 35th New Energy Auction, in 2021, most winning projects had prices of around 27 US$/ MWh for wind power and 31 US$/ MWh for solar, using the exchange rate at that time[62].

Another **upcoming revolutionary development will involve offshore wind energy**. With 7,367 km of coastline and 3.5 million km² of maritime space under its jurisdiction, Brazil possesses an extensive continental shelf that provides favourable conditions for the establishment and operation of projects aimed at generating offshore electric power.

In 2020, the "Offshore Wind Roadmap" published by EPE[63] indicated a potential for installing 700 GW of power in locations with depths of up to 50 meters, which is nearly 4 times the entire installed power generation capacity in Brazil.

In April 2022, Ibama reported that over 130 GW of offshore wind power projects were undergoing environmental licensing processes, highlighting the growing interest of entrepreneurs in this market. This interest extends not only to traditional players in the electricity market, such as Neoenergia (part of the Spanish group Iberdrola), but also to companies with a strong presence in the oil and gas sector, such as Shell, TotalEnergies, and

[62] CEBRI. (2022, May). Hydrogen and Energy Transition: Opportunities for Brazil.
[63] EPE. (2020). Roadmap Eólica Offshore Brasil. Retrieved from https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/roadmap-eolica-offshore-brasil

Petrobras. Petrobras has joined forces with Equinor, which already operates offshore wind farms in the UK, the northeastern United States, and Norway, to assess the feasibility of installing a wind farm in the Bacia de Campos, off the coast of Rio de Janeiro.[64]

The synergy between the already present oil sector, known for its expertise in building infrastructure in shallow, deep, and ultra-deep waters, is evident. The industry combines its experience in offshore projects with the desire to invest in renewable sources, driven by the pressure of international agreements for more sustainable energy policies, the financial market's interest in rewarding ESG practices, and the population's own demand for clean energy.

On one side, there is a vast availability of offshore wind resources, and on the other, there is a **clear market interest in investing in this type of energy**. It now falls upon policymakers to structure the pathways that will lead to this development. Brazil aims to approve a regulatory framework for offshore wind energy and green hydrogen by the end of 2023, informed the Minister of Mines and Energy, Alexandre Silveira.[65]

In the coming years, **Brazilian wind energy is expected to play a vital role**, not only in generating electricity and contributing to a more renewable energy mix in the country but also **in producing green hydrogen**. These steps are seen as a potential revolution, an efficient and real energy transformation that will contribute to leaving a more sustainable planet for future generations[66].

In addition to the potential of the offshore energy for hydrogen, Brazil has a **transport system that connects most of the country**. This allows to develop projects for hydrogen production connected to the grid, which, as well as enabling better dimensioning and greater deployment of electrolyzers, also permits trade of surplus electricity.

According to a McKinsey survey conducted in 2021[67], Brazil has a **competitive position in the green hydrogen sector**. The study indicates that the levelized cost of Brazilian green hydrogen (LCOH) is projected to be approximately 1.50 US$/kg H2 in 2030 and 1.25 US$/kg H2 in 2040. These costs are comparable to the best locations in the USA, Australia, Spain, and Saudi Arabia. The study also highlights that by 2030, projects located outside the grid may have around 10% higher LCOH than those connected to the grid. In terms of location, the Southeast region appears slightly more competitive than the Northeast, considering the current grid tariff configuration.

The same McKinsey survey estimates that the hydrogen market in Brazil could reach around 15-20 billion dollars by 2040, with a significant portion (US$ 10-12 billion) intended for the domestic market. This includes applications in cargo transport by trucks, the steel industry, and other

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[64] Portal Naval. Energia Eólica Offshore: Uma nova fronteira por Gustavo Morais. Retrieved from https://portalnaval.com.br/artigo/energia-eolica-offshore-uma-nova-fronteira-por-gustavo-morais-2/. Accessed on July 25, 2023.
[65] ABDIB - Associação Brasileira da Infraestrutura e Indústrias de Base. Brasil quer marcos para eólica offshore e hidrogênio verde ainda em 2023, diz ministro. Retrieved from https://www.abdib.org.br/2023/06/28/brasil-quer-marcos-para-eolica-offshore-e-hidrogenio-verde-ainda-em-2023-diz-ministro/. Accessed on July 25, 2023.
[66] O Setor Elétrico. Os caminhos da eólica offshore no Brasil e os primeiros passos do hidrogênio verde. Retrieved from https://www.osetoreletrico.com.br/os-caminhos-da-eolica-offshore-no-brasil-e-os-primeiros-passos-do-hidrogenio-verde/. Accessed on July 25, 2023.
[67] McKinsey & Company. Hidrogênio verde: Uma oportunidade de geração de riqueza com sustentabilidade para o Brasil e o mundo. Retrieved from https://www.mckinsey.com/br/en/our-insights/hidrogenio-verde-uma-oportunidade-de-geracao-de-riqueza-com-sustentabilidade-para-o-brasil-e-o-mundo/. Accessed on July 25, 2023.

industrial energy uses. Additionally, green hydrogen product exports to Europe and the US could account for another US$ 4-6 billion.

An international study conducted by the German consultancy Roland Berger[68] looks even further and suggests that Brazil has the **potential to become the world's largest producer of green hydrogen**, projecting annual revenues of R$150 billion (+/- US$ 30 billion) by 2050. Out of this, R$100 billion (+/- US$ 20 billion) is expected to come from exports.

The study emphasizes that Brazil possesses **ideal conditions for mass green hydrogen production** to drive the transition to a low-carbon economy, including a large supply of renewable energy, low marginal costs, and production potential beyond the domestic market's capacity. To meet global decarbonization goals, global hydrogen consumption will need to increase six-fold over the next 30 years, particularly in industrial applications and clean mobility.

The research identifies an opportunity for green hydrogen to attract a direct investment of R$600 billion in Brazil over the next 25 years, focusing on expanding the capacity of electrolyzers required for hydrogen production. As we have seen and will see further in this study, both companies and the government are beginning to pay attention to this matter, recognizing the immense potential and economic opportunities associated with green hydrogen in Brazil.

3.2 EXISTING GREEN HYDROGEN PROJECTS

In the last two years, dozens of projects for green hydrogen production have been announced in Brazil. According to a survey conducted by the National Institute of Clean Energy (Inel), these projects are estimated to attract over US$ 30 billion in investments.

While most of these projects are still in the feasibility study phase, some have already progressed beyond that, with memorandums of understanding signed with ports and state governments. These initiatives include both pilot projects and industrial-scale plants.

The projects are primarily concentrated in Brazil's port-industry regions, which offer several crucial advantages. Notably, these ports have the necessary infrastructure for hydrogen exportation, potential domestic consumers, and proximity to large offshore wind projects with substantial capacity for renewable energy production.

Here are 10 of the main initiatives for green hydrogen production in Brazil, listed according to the progress of the projects. There are eight commercial plants and two pilot projects[69]:

1. Unigel (State of Bahia)

   Unigel, known for fertilizer production, has already begun construction on what will be Brazil's first large-scale green hydrogen production plant. The facility will be located at the Camaçari Petrochemical Complex in Bahia. The company plans to invest US$ 1.5

[68] Valor International. (2023, January 22). Brazil has potential to be largest producer of green hydrogen, study shows. Retrieved from https://valorinternational.globo.com/business/news/2023/01/22/brazil-has-potential-to-be-largest-producer-of-green-hydrogen-study-shows.ghtml

[69] EPBR - Editora Brasil Energia. Hidrogênio verde: Conheça 10 projetos promissores em desenvolvimento no Brasil. Retrieved from https://epbr.com.br/hidrogenio-verde-conheca-10-projetos-promissores-em-desenvolvimento-no-brasil/. Accessed on July 25, 2023.

billion in the project by 2027, producing 100,000 tons of green hydrogen and 600,000 tons of green ammonia annually. For the initial phase, Unigel acquired three electrolyzers from ThyssenKrupp with a total capacity of 60 MW of energy.

Investment: US$ 1.5 billion.
Green hydrogen production: 100,000 tons/year
Green ammonia production: 600,000 tons/year
Electrolysis capacity (initial phase): 60 MW
Expected start: 2023
Full operation: 2027

2. Qair (State of Pernambuco)

   Qair Brasil, a French group, plans to invest approximately US$ 3.9 billion by 2032 in two plants at the Suape Industrial and Port Complex in Pernambuco. One plant will produce green hydrogen, and the other will produce blue hydrogen (from natural gas with carbon capture). The company was the sole participant in the bidding for the concession area at Suape and is awaiting contract signing. The project will be developed in four stages, reaching a capacity of 2,240 MW and producing 488,000 tons of hydrogen per year, of which 290,000 tons will be green hydrogen and 198,000 tons will be blue hydrogen.

   Investment: US$ 3.9 billion
   Green hydrogen production: 488,000 tons/year
   Blue hydrogen production: 198,000 tons/year
   Electrolysis capacity: 2.2 GW
   Expected start: 2025
   Full operation: 2032

3. Qair (State of Ceará)

   Qair aims to replicate a similar project at the Pecém Port-Industrial Complex (CIPP) in Ceará. Besides the US$ 3.9 billion investment in hydrogen plants, Qair will invest an additional US$ 3 billion in a 1.2 GW offshore wind project near Pecém, providing the renewable energy required for green hydrogen production.

   Investment: US$ 6.9 billion
   Green hydrogen production: 488,000 tons/year
   Electrolysis capacity: 2.2 GW
   Offshore wind capacity: 1.2 GW
   Expected start: not disclosed

4. Casa dos Ventos and Comerc (State of Ceará)

   Casa dos Ventos and Comerc Eficiência signed a pre-contract with the Pecém Port-Industrial Complex in Ceará to install a green hydrogen and green ammonia production facility. The estimated investment is about US$ 4 billion until 2030, with the first phase of operation expected to start in 2026. At full operational capacity, the plant will have an electrolysis capacity of 2.4 GW, producing over a thousand tons of hydrogen per day and 2.2 million tons of green ammonia per year.

Investment: US$ 4 billion
Green hydrogen production: 365,000 tons/year
Green ammonia production: 2.2 million tons/year
Electrolysis capacity: 2.4 GW
Expected start: 2026
Full operation: 2030

5. Fortescue (State of Ceará)

   The Australian mining giant, Fortescue, plans to invest US$ 6 billion in a green hydrogen plant at the Pecém Complex. The global goal is to produce 15 million tons per year of green hydrogen by 2030, increasing to 50 million tons per year in the following decade.

   Investment: US$ 6 billion
   Green hydrogen production (global target): 15 million tons/year
   Expected start: 2025
   Full operation: 2027

6. AES (State of Ceará)

   AES Brasil has a pre-contract with the Pecém Port-Industrial Complex for feasibility studies on the production of up to 2 GW of hydrogen through electrolysis and up to 800,000 tons of green ammonia per year, with plans to export the production to European countries. The investment is estimated at US$ 2 billion within the first five years.

   Investment: US$ 2 billion
   Green ammonia production: 800,000 tons/year
   Electrolysis capacity: 2 GW
   Expected start: to be defined

7. White Martins (State of Pernambuco)

   White Martins, part of the German Linde Group, began producing green hydrogen on a medium scale in Pernambuco in December 2022, with an expected annual output of 156 tons of H2V (green hydrogen). The company aims to expand production and supply, with additional projects in Rio de Janeiro, Rio Grande do Sul, and Ceará, using electrolysis to produce hydrogen from renewable sources.

   Investment: not disclosed
   Green hydrogen production: 156 tons/year
   Expected start: 2022

8. Green Hydrogen Pilot Projects Eletrobras Furnas (States of Goiás and Minas Gerais)

   Eletrobras/Furnas inaugurated a pilot project for green hydrogen production at the Itumbiara Hydropower Plant, located on the border between Goiás and Minas Gerais.

With investments of approximately R$ 45 million, the project has already produced around 1.5 tons of green hydrogen. The initiative aims to test the storage of seasonal and intermittent energy and its integration into the National Interconnected System (SIN).

Investment: R$ 45 million
Green hydrogen production so far: approximately 1.5 tons
Energy generation capacity: 1 MW
Expected start: 2021

9. EDP (State of Ceará)

   EDP Brasil inaugurated its green hydrogen pilot project at the Pecém Thermal Power Complex, where it operates a coal-fired plant. The project, with an investment of R$ 42 million, is expected to be completed by June 2024. The plant includes a solar unit with a capacity of 3 MW and an electrolyzer module capable of producing 250 m3/h of hydrogen gas.

   Investment: R$ 42 million
   Green hydrogen production: 250 Nm3/h
   Electrolysis capacity: 3 MW
   Expected start: 2022
   Full operation: 2024

10. Shell/Raízen/Hytron/Toyota (State of São Paulo)

    In a unique partnership, Shell, Raízen, Hytron, University of São Paulo (USP), and Senai CETIQT, along with Toyota, plan to invest in plants dedicated to hydrogen production from ethanol and a refueling station for buses in the Cidade Universitária area in São Paulo. The agreement includes the construction of two plants capable of producing 5 kg/h of hydrogen, followed by a tenfold increase to 44.5 kg/h. The proposal is to use hydrogen to replace diesel in one of the campus buses, equipped with fuel cell technology. The green hydrogen production from ethanol could be used to decarbonize the local industry and heavy transport. The project will be financed by Shell Brasil, with an investment of approximately R$ 50 million.

    Investment: R$ 50 million
    Green hydrogen production: 390 tons/year
    Expected start: 2023

4. MAIN INSERTION NICHES OF HYDROGEN IN BRAZIL

There is a global consensus on the need to promote actions for decarbonization in major activities and sectors responsible for greenhouse gas emissions. However, this is not a straightforward process and varies among countries due to differences in energy matrices, technological maturity, public policies, investment capacity, and the consumer market.

In line with developed countries, decarbonization targets will drive Brazil to replace fossil fuels currently used in industry and transportation with non-emitting or low CO2-emitting alternatives. Unlike developed countries, the industrial and transportation sectors are the largest carbon emitters in Brazil, accounting for 47% and 21%, respectively[70].

In 2019, the industry accounted for 30.7% of the total energy consumed, with renewable energies representing 58% of its energy consumption. Among fossil fuels, coal led with 13.5% of the total, followed by natural gas with 10.5%. Hydrogen has the potential to replace these fossil fuels in the industrial sector.

Regarding the transportation energy mix, it represented 32.7% of the country's total consumption, with 25% coming from renewable fuels (ethanol and biodiesel, accounting for 20.6% and 4.5% respectively). Diesel and gasoline were the dominant fuels, constituting 41.9% and 25.3% respectively, while natural gas held a 2.4% share. Hydrogen can gradually substitute fossil fuel consumption in the transportation sector, particularly with the introduction of Fuel Cell Electric Vehicles (FCEVs). However, the development of the FCEV market depends on establishing a hydrogen refueling infrastructure, which presents a challenge requiring significant investments.

Currently, Brazil has a surplus of natural gas, and production is expected to increase due to pre-salt reserves. Consequently, gray hydrogen, which serves as a transition to green hydrogen, could be employed to establish or expand hydrogen markets. However, considering the existing gas pipeline network primarily located near the coast, this production may not reach inland markets in the short to medium term. This presents an opportunity for the installation of smaller-scale green hydrogen generation through electrolyzers[71].

Among the industrial sectors that are major (potential) consumers of hydrogen, the petroleum refining and ammonia production industries stand out. However, there are opportunities for hydrogen utilization in other industries, such as cement, steel production, mining, among others. Additionally, apart from industrial and large-scale mobility applications, hydrogen's energy usage should also be considered.

[70] IEA – INTERNATIONAL ENERGY AGENCY. "Global Hydrogen Review 2021." Available at: https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf. Accessed on November 29, 2021.

[71] EPE – ENERGY RESEARCH COMPANY. "Decennial Energy Expansion Plan 2031." 2022. Available at: https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/Documents/PDE%202031_RevisaoPosCP_rvFinal_v2.pdf.

4.1 INDUSTRIAL SECTORS[72]

4.1.1 Oil industry

In the specific case of petroleum refining, the production of gray hydrogen within the refinery is simultaneous with its consumption in the hydro-treatment and hydrocracking processes. The former involves the removal of sulfur and nitrogen impurities, while the latter pertains to the upgrading of heavy refining fractions. Additionally, Petrobras employs the H-Bio process, which involves the hydro-treatment of vegetable oil together with previously treated diesel oil. This process results in a high-quality diesel oil with low sulfur content, and it also includes light oils in the final product

Both cases result in an increased demand for hydrogen, and the natural trend would be a shift from gray hydrogen production to technologies that prioritize CO2 capture (blue hydrogen) or hydrogen production from plastic. Due to the volume of captured CO2, there would be a need to establish both a destination and a transportation method for it. Additionally, it is not ruled out that in the future, hydrogen producers from other sources could act as suppliers of hydrogen to petroleum refining units.

The main barrier to replacing gray hydrogen with green hydrogen lies in the volume required for current operations or to meet the growing demand from petroleum processing companies. This limitation is not unique to Brazil and is observed globally.

4.1.2 Fertilizer industry

The production of nitrogen fertilizers, along with petroleum refining, accounts for the largest portion of hydrogen consumption worldwide. Nitrogen fertilizers rely on the production of anhydrous ammonia (NH3) through the reaction of hydrogen and nitrogen available in the environment (Haber-Bosch process). As a result, ammonia production requires significant volumes of hydrogen, which is primarily produced through steam methane reforming (from natural gas).

Brazil has companies that produce nitrogen fertilizers (Petrobras, Fosfértil, Braskem, and Proquigel), but the Brazilian agribusiness is very dependent on fertilizer imports, and it is estimated that the nitrogen-based fertilizers alone account for 60% of the required volume. The challenge is exacerbated by the fact that these products are subject to international pricing.

Furthermore, the fertilizer market heavily relies on transportation logistics, which indicates the need to establish production units close to major consumption centres. In this scenario, it would also be necessary to produce the main input (ammonia) locally for nitrogen fertilizer manufacturing. The main obstacles would be the absence of natural gas pipelines near the consumption points for blue hydrogen production and the cost of local green hydrogen production.

[72] A economia do hidrogênio : transição, descarbonização e oportunidades para o Brasil /organização Nivalde de Castro ... [et al.]. - 1. ed. - Rio de Janeiro : E-papers, 2023.

4.1.3 Mining industry

The opportunities for using hydrogen in the mining industry overlap with those described in the mobility sector, aiming to decarbonize and reduce costs related to diesel consumption and transportation for the large trucks used in mines and railway transport of ore.

In Brazil, there are research and development groups interested in studying the possibility of using hydrogen blended with diesel, with minimal modifications to the current engines, to reduce consumption and emissions from truck engines. Hydrogen production in remote mining locations could be achieved through electrolyzers connected to renewable energy sources for electricity generation.

Regarding the specific case of ore railway transport, there are alternatives for locomotive fuels as well as electrification options using fuel cells. For long distances, logistics for refueling along the route or the use of hydrogen tanks as part of the train must be studied. As of now, there are no demonstration projects for ore trains utilizing fuel cells.

4.1.4 Steel industry

In general terms, the steel production process in a blast furnace begins with the mixing of iron ore with coke and limestone, resulting in iron (pig iron) with a high carbon content and the consequent emission of CO2. In a second stage, this pig iron is transferred to a furnace where, through the injection of oxygen, the carbon present in the iron is removed, leading to additional CO2 emissions. In this cycle, including the reduction and combustion processes, an average of 1.73 tons of CO2 is emitted per ton of steel produced[73].

All technologies aimed at employing hydrogen in the steel industry for the decarbonization of the sector need to be evaluated from an economic perspective and compared with those that prioritize carbon capture and storage (CCUS). When analysing the possibility of using hydrogen in steel refining or rolling operations, logistical aspects should also be considered, whether it's about local hydrogen production or its importation through pipelines, given the high volume required.

Brazil ranks ninth in steel production among global producers (32.6 million tons of crude steel in 2019), with steel mills distributed across ten states of the country. The mills are classified into three categories depending on their involvement in the production chain. Integrated mills encompass all production processes (reduction, refining, and rolling), semi-integrated mills operate in refining and rolling, and non-integrated mills participate only in one phase of production (processing or reduction). Integrated mills might be the most inclined to use hydrogen in their production processes, but due to being a highly competitive market, economic factors could pose a barrier.

4.1.5 Cement industry

The cement industry is one of the industrial segments that simultaneously have high energy consumption and high CO2 emissions. These emissions primarily come from the limestone

[73] Bartlett, J., & Krupnick, A. (2021). The potential of hydrogen decarburization on reducing emissions in iron and steel production. Retrieved from https://www.resources.org/common-resources/the-potential-of-hydrogen-for-decarbonization-reducing-emissions-in-iron-and-steel-production/

calcination stage (50%), the heat generation for raw material processing (40%), and the remaining auxiliary services[74]. The cement industry seeks to diversify the range of fuels used, with approximately 85% of them being of fossil origin in Brazil, predominantly petroleum coke[75].

In all countries, but particularly in Brazil due to the characteristics of the construction industry and the demand for both housing and infrastructure projects, the cement industry plays an important role in decarbonization efforts. There are actions related to expanding the use of alternative fuels (such as charcoal, used tires, industrial and oily residues, plastics, biomass, etc.) in thermal substitution[76]. Studies are also being elaborated to assess the possibility of mixing hydrogen with natural gas or biomass for furnace heating, and the utilization of hydrogen along with CCUS technologies for producing synthetic fuels through Power-to-Gas (PtG) technologies[77].

Potential barriers that could hinder the use of hydrogen include, besides the technological aspects of production, the various alternatives for reducing fossil fuel consumption in thermal substitution, the impact of local hydrogen production costs on the final cost of cement in case of partial replacement of current fossil fuels, and the destination and market for products derived from combining hydrogen with CO2 from capture systems.

In the cement industry, H2V can provide energy to replace coal and gas, although this integration is not considered the primary solution for the sector. The use of H2V for heat generation was previously identified in the Cement Technological Roadmap, which indicates the potential for reducing carbon emissions from the Brazilian cement industry by 2050[78]. Among the more moderate possibilities, the industry points out that the carbon from CO2 capture processes, obtained through blue hydrogen production, could be used in the clinker production. Additionally, the use of H2 for heating could be considered as an alternative, but its applicability would depend on the feasibility of adapting the clinker production process to use hydrogen as the main fuel in the furnace.

The cement sector has a significant carbon footprint, ranking as the second-largest industrial emitter, following only the steel industry both in Brazil and worldwide. Nevertheless, the use of hydrogen as a decarbonization solution is currently only being observed by the sector.

According to the National Union of the Cement Industry (SNIC), the cement industry predominantly uses petroleum coke, with 50% of the cost coming from fuel combustion or electricity usage. As a result, CO2 emissions are inherent in the process.

Despite innovative Technologies and CCUS representing 9% of the CO2 Reduction potential in the mentioned Roadmap, this kind of technology is expensive. Thus, as the costs of H2V decline, making it competitive, the cement sector faces an opportunity for decarbonization, considering

[74] Faria, D. G. (2018). Captura, Armazenamento e Utilização do Dióxido de Carbono na Indústria do Cimento [Master's thesis, Departamento de Engenharia Química, Universidade Federal de Minas Gerais]. Retrieved from https://repositorio.ufmg.br/bitstream/1843/32406/1/Disserta%c3%a7%c3%a3o%20de%20mestrado%20-%20D%c3%a9bora%20Faria%20-%20Vers%c3%a3o%20Final.pdf
[75] Visedo, G., & Pecchio, M. (Eds.). (2019). ROADMAP tecnológico do cimento: potencial de redução das emissões de carbono da indústria do cimento brasileira até 2050. Rio de Janeiro: SNIC.
[76] Visedo, G., & Pecchio, M. (Eds.). (2019). ROADMAP tecnológico do cimento: potencial de redução das emissões de carbono da indústria do cimento brasileira até 2050. Rio de Janeiro: SNIC.
[77] Global Cement. (2020). Green hydrogen for grey cement. Retrieved from https://www.globalcement.com/news/item/11061-green-hydrogen-for-grey-cement
[78] ABCP. (2023). Roadmap Tecnológico do Cimento Brasil [Ebook]. Retrieved from https://abcp.org.br/roadmap-tecnologico-do-cimento-brasil-ebook/

that energy accounts for 50% (35% fuel and 15% electricity) of cement production costs. However, this reduction would need to be substantial, as H2 would compete with currently utilized materials since, due to the low specific value of cement, the industry burns various materials (even used tires).

4.2 TRANSPORTATION SECTOR

Electric mobility is closely related to the commitments made by countries to achieve the goal of reducing greenhouse gas emissions, which can promote both the reduction of air pollution and global warming. Globally, the transportation sector accounted for a significant portion of greenhouse gas emissions in 2019 (17%), second only to the electricity and heat generation sector (33%)[79].

In Brazil, urban passenger transportation by buses represents the most important mode of daily commuting, especially in capital cities and municipalities located in metropolitan areas. For example, the metropolitan area of São Paulo (39 municipalities) is the sixth-largest in the world in terms of population, with about 21 million inhabitants, served by 43.000 urban buses, which are the main contributors to urban pollution. Similar situations exist in other cities and explain Brazil's leadership in the bus manufacturing market, with an annual production of about 30.000 units.

Based on this scenario, Brazil initiated the Hydrogen Fuel Cell Buses for Urban Transportation in Brazil project in November 2000, financed by the Global Energy Facility (GEF) and the Brazilian government (FINEP) to conduct a demonstration project, in collaboration with Brazilian industries, to evaluate the performance of hydrogen fuel cell buses (2 x 75 kW, 30.8 kg H2 storage), including the operational infrastructure. Three buses were constructed and operated throughout the project period. The project, concluded in 2017, was considered successful from an operational perspective and laid the foundation for the development, production, and operation of fuel cell buses in Brazil. The results provided the basis for expanding the project to a commercial scale[80].

Another project developed at UFRJ (Federal University of Rio de Janeiro) resulted in the construction and operation of a hybrid battery/fuel cell bus, with the possibility of recharging the battery bank from the grid, the fuel cell, and a regenerative braking system. As mentioned earlier, the first version of this vehicle was completed in 2010, a second version was presented at the Rio+20 Conference in 2012, and the third version was demonstrated at the 2016 Olympic Games in Rio de Janeiro, under pre-commercial conditions[81].

Among the ongoing projects some involve adding hydrogen in the form of a mixture with current fuels to internal combustion engines or generating hydrogen onboard through ethanol reforming. In 2019, Unicamp (State University of Campinas) and Nissan also signed a service contract for a study on using bioethanol as an option for electric mobility. The Japanese manufacturer financed the project with the intention of developing a prototype vehicle with a

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[79] Climate Watch. (2022). Historical GHG Emissions. Washington, DC: World Resources Institute. Retrieved from https://www.climatewatchdata.org/ghg-emissions
[80] Climate Watch. (2022). Historical GHG Emissions. Washington, DC: World Resources Institute. Retrieved from https://www.climatewatchdata.org/ghg-emissions
[81] Miranda, P. E. V., Carreira, E. S., Icardi, U. A., & Nunes, G. S. (2017). Brazilian hybrid electric-hydrogen fuel cell bus: Improved on-board energy management system. International Journal of Hydrogen Energy, 42(19), 13949-13959.

solid oxide fuel cell (SOFC) that operates on energy generated from ethanol without combustion, at the Genome and Bioenergy Laboratory at Unicamp[82].

Therefore, the basis exists for the development of a domestic hydrogen fuel cell bus industry. The average hydrogen consumption for a 12-meter urban bus, with 29 seated passengers, low floor, and a maximum speed of 85 km/h, ranges from 7 to 10 kg H2/100 km. In general, urban buses in major Brazilian cities cover daily routes of less than 300 km. The operation of a fleet of such buses would require a centralized refuelling station at the concessionaires' depots and a complete infrastructure for local hydrogen production and storage.

In general, the barriers that can be identified for the widespread use of hydrogen in vehicle mobility (cars, buses, trucks) with fuel cells would be the current cost of the complete propulsion system and the existence of a hydrogen refuelling network.

In the automotive segment, the Rota 2030 Program[83] is an initiative by the federal government aimed at stimulating the development of the domestic industry through reduced taxes and other benefits for R&D projects in the sector. The program establishes public policies for the development of the domestic automotive sector through effective interaction between academia, companies, and the government. By promoting projects at all Technology Readiness Levels (TRL 1 to 9), the program encourages proposals within one of its lines (Line V) for the production of new technologies related to biofuels, vehicle safety, and alternative propulsion to combustion.

In this context, the great opportunity for hydrogen insertion in the automotive market has been promoted through the Biofuels Axis. The program incentivizes projects aimed at developing Fuel Cell Electric Vehicles (FCEVs) with dedicated electric propulsion, whose energy source comes from fuel cells, mainly hydrogen, or liquid fuels, when reformers are present. In these vehicles, similar to conventional ones, electricity powers the vehicle's electric motor derived from hydrogen. Within this line, there are several configurations for supplying and storing hydrogen – including from renewable sources (e.g., ethanol).

The Rota 2030 Program currently approves and finances three projects in the biofuels axis:

- The first focuses on the dual-fuel technology in compression-ignition engines using renewable diesel (HVO/Farnesane) with ethanol, hydrogen, or biogas. The goal is to increase fuel conversion efficiency, reduce pollutant emissions, and develop technology for application in FPT Industrial engines.

- The second project involves a study on energy efficiency in flex engines with hydrogen enrichment obtained through onboard catalytic reforming. The aim is to develop a monolithic catalyst for ethanol or gasoline reforming to produce hydrogen, numerical simulation in engine simulation software, and testing on a dynamometer bench with a single-cylinder research engine to evaluate performance and pollutant emissions. The project, in partnership with AVL South America and Sabó Indústria e Comércio de Autopeças, involves various universities, such as Fundação Educacional Inaciana (FEI),

[82] Sugimoto, L. (2019). Unicamp, Nissan e o carro movido com eletricidade gerada por etanol. Unicamp. Retrieved from https://www.unicamp.br/unicamp/noticias/2019/04/26/unicamp-nissan-e-o-carro-movido-com-eletricidade-gerada-por-etanol
[83] Ministério da Economia. (2023). Rota 2030: Mobilidade e Logística. Retrieved from https://www.gov.br/produtividade-e-comercio-exterior/pt-br/assuntos/competitividade-industrial/setor-automotivo/rota-2030-mobilidade-e-logistica

Universidade Federal de Minas Gerais (UFMG), Instituto Nacional de Tecnologia (INT), and Universidade Federal de São Carlos (UFSCar).

- The third project, titled "Increasing Vehicle Propulsion Efficiency through Onboard Hydrogen Generation: From Reformer Development to Propulsion System Testing," aims to develop a test bench to evaluate the efficiency of catalysts for onboard hydrogen generation through steam reforming using commercial hydrated ethanol. In this case, hydrogen would be reinjected into the combustion chamber to assist fuel combustion, reducing fuel consumption, and consequently, exhaust gas emissions. The project is being developed by PUC-Rio and IPEN in partnership with companies such as Ipiranga Produtos de Petróleo S.A., Mercedes-Benz do Brasil Ltda., Stellantis, Umicore, and Robert Bosch Ltda.

Environmental and economic motivations are driving the automotive industry to consider electric vehicles powered or enriched with hydrogen as one of the promising solutions in the relatively near future. The Rota 2030 Program, therefore, aims to assist Brazil in overcoming technological and commercial viability barriers. With a vision of future scenarios, the program represents an interesting strategy for achieving success in the sector, creating new competencies, and training human resources for the domestic industry, allowing Brazil to participate in global process development.

4.3 ENERGY GENERATION SECTOR

The main applications are related to the possibility of producing hydrogen from renewable sources. However, as intermittent renewable sources are increasingly integrated into electricity generation systems, hydrogen production through water electrolysis can contribute to stabilizing the balance between production and consumption by producing and storing hydrogen. Hydrogen can also play other roles in the energy sector, such as being used as a fuel in combination with natural gas for gas turbines (Power-to-Power), producing synthetic methane and direct injection in combustion engines (Power-to-Gas), and producing biofuels for electric mobility (Power-to-Fuel).

In Brazil, there are pioneering projects for the energetic use of hydrogen in Itaipu, AES Tietê, Furnas, and Energy Assets do Brasil Ltda:

- At Itaipu (Itaipu Technological Park), the hydrogen production plant inaugurated in 2014 aims to utilize secondary energy or the energy released at the power plant to produce hydrogen through electrolysis. Besides generating about 70kg of hydrogen between March and October 2015, the plant has a 6kW fuel cell capable of providing electricity for up to 285 lamps of 70W. The plant operates in a simple and automated manner, with the goal of scaling up and replicating the technology's use in other utilities[84].

- The AES Tietê project, developed under the ANEEL R&D program, seeks to develop converters for using hydrogen/diesel blends in generator sets[85]. Meanwhile, the Furnas project for a green hydrogen generation plant at the Itumbiara hydroelectric power

[84] ABRAPCH – Associação Brasileira de Centrais Hidrelétricas PCH e CGH. (2016). Itaipu aprova testes de unidade piloto de hidrogênio. Retrieved from https://abrapch.org.br/2016/02/18/itaipu-aprova-testes-de-unidade-piloto-de-hidrogenio/
[85] AES Brasil. (2020). AES Tietê investe em projeto de P&D ANEEL para geração de energia com hidrogênio. Retrieved from https://www.aesbrasil.com.br/pt-br/aes-tiete-investe-em-projeto-de-pd-aneel-para-geracao-de-energia-com-hidrogenio-0

plant in Goiás aims to expand the storage capacity of the national integrated system (SIN) through the synergy between hydrogen production by electrolysis and photovoltaic generation[86].

- The Energy Assets do Brasil project, executed by PUC-Rio and also carried out under the ANEEL R&D program, involves an autonomous system for generating electricity from ethanol reforming to obtain hydrogen, storage, and later conversion into electrical energy in a fuel cell. In the same vein, researchers from PUC-Rio and Energy Assets do Brasil have been working on distributed generation systems since 2015, with funding from the ANEEL R&D clause. One of their projects focuses on developing a simulator capable of evaluating the energy and economic aspects of a hybrid system for electricity and heat generation, including cogeneration, for isolated consumers. This system consists of a reformer and a PEMFC (Proton Exchange Membrane Fuel Cell) fueled by ethanol and photovoltaic panels, with the possibility of storing hydrogen and electricity in batteries[87].

Similarly, another project involves developing a simulator to assess technically (from an energy and exergy perspective), environmentally, and economically, a hybrid system for electricity and heat generation, including cogeneration, connected to the grid. This system is composed of a fuel cell (either PEMFC or SOFC - Solid Oxide Fuel Cell) fueled by natural gas and/or biogas, photovoltaic panels, and a battery bank, under different loads[88].

Both projects have shown the technical feasibility and environmental benefits of the systems, but economic viability is still dependent on reducing equipment costs.

The aforementioned projects related to the energetic use of hydrogen present opportunities for its expansion. However, they also reveal the need for regulatory frameworks and the removal of barriers related to storage and transportation, as well as cost-related concerns.

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[86] Furnas. (2021). Planta de geração de hidrogênio verde é inaugurada por Furnas em Itumbiara (MG). Retrieved from https://www.furnas.com.br/noticia/103/noticias/1759/planta-de-geracao-de-hidrogenio-verde-e-inaugurada-por-furna

[87] Silva, A. C. S., et al. (2019). Feasibility Study of an Off-Grid Hybrid Solar-Ethanol-Hydrogen Electrical Generation System. Paper presented at Hypothesis XIV, April 24-29, 2019, Foz do Iguaçu.

[88] Gabriel, R. O., Braga, S. L., Pradelle, F., Serra, E. T., & Vieira, C. L. C. S. (2022). Numerical Simulation of an on-Grid Natural Gas PEMFC – Solar Photovoltaic MicroCHP Unit: Analysis of the Energy, Economic and Environmental Impacts for Residential and Industrial Applications. Technology and Economics of Smart Grids and Sustainable Energy, 7(5).
Gabriel, R. O., Laya Junior, E. S., Braga, S. L., Pradelle, F., Serra, E. T., & Vieira, C. L. C. S. (2022). Technical, economic and environmental analysis of a hybrid CHP system with a 5 kW PEMFC, photovoltaic panels and batteries in the Brazilian scenario. Energy Conversion and Management, 269, 16042.

5. INTERNATIONAL INVESTMENTS, PARTNERSHIPS AND EXPORTS

As already mentioned, low-carbon hydrogen can be one of the driving forces behind the next phase of clean energy transitions in Latin America and the world. Chile aims to produce and export the most competitive hydrogen in the world from renewable electricity by 2030, and many countries in Latin America, including Brazil, share the conditions that could make the region a global leader in low-carbon hydrogen production. Eleven countries in the region have published or are preparing national strategies and roadmaps for hydrogen: Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, El Salvador, Panama, Paraguay, Trinidad and Tobago, and Uruguay[89].

Offshore wind ports are preferred models for H2V in Brazil, as coastal industrial clusters can serve as gateways for the construction of hydrogen hubs. The production of H2V from renewable sources such as solar and wind energy represents an opportunity for sustainable socio-economic development in the Northeast of Brazil, thanks to the low costs of renewable energy generation, which help H2V become competitive.

5.1 STRATEGIC LOCATIONS

In this section of the study, we will take a closer look at the locations that have been identified as strategic sites for green hydrogen production. These locations have already captured the attention of both domestic and international investors.

The investments announced for the construction of H2V production plants in Brazil have now surpassed $27 billion, with the majority of these investments concentrated in ports – Pecém in Ceará, Suape in Pernambuco, and Açu in Rio de Janeiro. These ports encompass a range of strategic factors that contribute to the development of the new H2V supply chain, including export logistics, proximity to industrial hubs, and access to renewable energy sources.

5.1.1 Port of Suape – Pernambuco

The Suape Industrial Port Complex, located in Pernambuco, houses one of Brazil's main refineries, Abreu e Lima (RNEST), in addition to over 150 industries currently operating within the port complex, including petrochemical, food, cement, and steel sectors. Initially producing blue hydrogen, the Suape port will invest in H2V, with solar energy as its primary source, as Pernambuco has a licensed solar capacity of 3 GW, but only 167 MW in operation. The Suape port aims to position itself as an exporter, both in terms of ammonia and H2V, while also meeting the internal demand of companies already established at the port.

The government of Pernambuco will conduct an auction for H2V to develop the H2V propulsion platform in the region. The port is strategically located near the major northeastern capitals, facilitating the domestic distribution of H2V production, particularly green ammonia for the agricultural sector. The produced ammonia can be supplied to the low-carbon agriculture market, supporting regions like Petrolina, known for fruit production, and the Matopiba region –

[89] IEA. (2021). Hydrogen in Latin America. Paris: IEA. Retrieved from https://www.iea.org/reports/hydrogen-in-latin-america

an acronym referring to the agricultural belt formed by the states of Maranhão, Tocantins, Piauí, and Bahia – which stands out for its grain and fiber production, especially soybeans, corn, and cotton[90].

The Suape Industrial Port Complex also aims to innovate in the production of green hydrogen through a TechHub. This initiative is developed in partnership with the Chinese company CTG, the National Department of Senai (non-profit secondary vocational schools), Senai Pernambuco, and the state government. The goal is to transform the port into a space for research, development, and innovation with a focus on green hydrogen. Currently, the complex is equipped to accommodate 42 projects[91].

5.1.2 The Pecém Complex – Ceará

The Pecém Complex is the outcome of a collaborative venture established between the State Government of Ceará, situated in northeastern Brazil, and the Port of Rotterdam. Encompassing an expansive area exceeding 19.000 hectares, the Pecém Complex boasts a robust infrastructure and a strategically advantageous geographical location. It particularly shines as the epicenter of green hydrogen initiatives in Brazil, as it hosts the nation's pioneering projects in this domain.

The Pecém Complex comprises 3 pivotal components:

- the Industrial area, home to some of the key manufacturing units in the Brazilian northeast;
- the Pecém Port, a world-class offshore terminal that managed over 22 million tons in 2021; and
- an Export Processing Zone (ZPE), the inaugural operational export processing zone in Brazil, now expanded with an additional area of more than 1,900 hectares to accommodate fresh investments[92].

Pecém has attracted Dutch interest due to its rapid growth as a port. Thanks to a strategic partnership with the Port of Rotterdam, the port has gained increased capacity and efficiency to compete in the international market. Since 2018, the Pecém Complex has leveraged the expertise and know-how of its international partner for the joint management of the industrial and port complex, thereby expanding Ceará's ability to attract even more international investments, not only in the port sector but also in infrastructure and the establishment of new industries in the region.

The Port of Rotterdam holds a 30% stake in the venture and holds positions in the Executive Board, Fiscal Council, and Administration. The total investment made by the Dutch amounts to

[90] Machado, N. (2021, November 17). As promessas da COP26 para pagar a conta do hidrogênio. EPBR. Retrieved from https://epbr.com.br/as-promessas-da-cop26-para-pagar-a-conta-do-hidrogenio/. Accessed on August 2, 2023.

[91] Brasil61. Pernambuco TechHub do Complexo de Suape promete inovação na produção de hidrogênio verde. Retrieved from https://brasil61.com/n/pernambuco-techhub-do-complexo-de-suape-promete-inovacao-na-producao-de-hidrogenio-verde-pind233992. Accessed on August 3, 2023.

[92] Rosana Cavalcante de Oliveira R. (2022, August). Panorama do Hidrogênio no Brasil. IPEA.

75 million Euros. In the future, this partnership will also be utilized for exporting hydrogen to Europe[93].

The Pecém Industrial and Port Complex (CIPP) also has potential consumers of green hydrogen: steel, fertilizers, and petrochemicals. The following companies within the Pecém complex are listed as potential partners in the production/consumption of H2V: Vale, Enel, Phoenix, Votorantim, Cimento Apodi, EDP, Eneva, White Martins/Linde, Companhia Sulamericana de Cerâmica, Termo Ceará and Aeris Energy.[94]

The green hydrogen HUB situated within the port is poised to be a transformative force for both existing companies located in the port and potential new investors. Presently, the Pecém Green Hydrogen HUB has successfully secured 22 Memoranda of Understanding (MoUs), all geared towards the production and export of green hydrogen. Notably, two of these MoUs have progressed into pre-contract agreements. The most recent of these agreements was inked with the North American multinational AES in September of 2022. This accord envisions the establishment of a facility for the production and commercialization of H2V and its derivatives within the Export Processing Zone (ZPE). In June of the same year, the Pecém Complex had previously entered into a pre-contract agreement with the Australian multinational Fortescue Metals Group, a prominent global player in the iron ore industry. Although the commencement dates for installation work vary, Pecém's projections indicate the initiation of green hydrogen production in 2025, with an anticipated volume of 1.3 million tons by 2030.[95]

In this context, EDP Brasil produced the first molecule of green hydrogen (H2V) in December 2022 at its new unit located in Pecém. The development of this plant marks a significant milestone for clean energy generation in the country and represents the initial strategic phase of the H2 Pilot Project. The Pecém plant comprises a solar facility with a capacity of 3 MW and an electrolyzer module for renewable fuel production, with the capability to produce 250 cubic meters of gas per hour.

EDP Brasil's CEO, João Marques da Cruz, explained the reasons for choosing Ceará to house the company's first H2V molecule: "Ceará possesses strategic attributes that position it to lead the introduction of green hydrogen in the country, whether due to its exceptional solar and wind potential, which are crucial for the production, or its location and excellent infrastructure for exporting this product to the international market," he stated.[96]

5.1.3 Port do Açu – Rio de Janeiro

Porto do Açu Operações, the administrator and landlord of the port, is responsible for managing and developing Porto do Açu, the largest industrial port complex in Latin America, housing 21 different companies. The port is a partnership between Prumo Logística, controlled by investment funds EIG and Mubadala, and the Antwerp-Bruges International Port[97]. Porto do

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[93] Porto de Roterdã como parceiro. Retrieved from https://www.complexodopecem.com.br/porto-de-roterda-como-parceiro. Accessed on August 03, 2023.
[94] Rosana Cavalcante de Oliveira R. (2022, August). Panorama do Hidrogênio no Brasil. IPEA.
[95] Pecém Industrial and Port Complex Presents its Green Hydrogen HUB at the Hydrogen Americas Summit 2022 . Hydrogen-Central. Retrieved from https://hydrogen-central.com/pecem-industrial-port-complex-presents-green-hydrogen-hub-hydrogen-americas-summit-2022/. Accessed on August 3, 2023.
[96] Primeira molécula de hidrogênio verde é produzida no Ceará; veja detalhes. O Povo. Retrieved from https://www.opovo.com.br/noticias/economia/2022/12/16/primeira-molecula-de-hidrogenio-verde-e-produzida-no-ceara-veja-detalhes.html. Accessed on August 3, 2023.
[97] Porto do Açu. Retrieved from https://portodoacu.com.br/nossa-empresa/. Accessed on August 3, 2023.

Açu is also situated near future offshore wind farms in the seas of Rio de Janeiro and Espírito Santo. The Ventos do Atlântico project, for example, is the country's second-largest, with 371 wind turbines and just over 5 GW of capacity. It is also the first port in Brazil to implement a vessel traffic service (VTS).[98]

Located in Rio de Janeiro, the port currently produces blue hydrogen from a fossil source (typically natural gas). The carbon emitted during this process is captured and stored to neutralize emissions. The port aims to leverage its expertise and infrastructure in the oil and gas industry during the transition to H2V.

The Australian mining company Fortescue announced its interest in establishing a green ammonia production plant exclusively for export, based on a feasibility study for a 300 MW H2V plant. This plant is projected to produce 250,000 metric tons of green ammonia, serving as a foundation for agricultural fertilizers. The port anticipates receiving investments of R$ 16.5 billion for the implementation of thermal power plants, pipelines, oil pipelines, an oil tank farm, a natural gas processing unit (UPGN), and more. Furthermore, Porto do Açu has signed agreements with companies aiming to produce H2V.[99]

In May 2022, Shell Brasil and Porto do Açu signed a Memorandum of Understanding (MoU) to jointly develop a pilot plant for green hydrogen generation at the port's facilities. This pioneering project in Brazil will function as a research laboratory to foster learning, conduct decarbonization tests, and drive this industry in the country. The resources for constructing the unit come from the Research, Development & Innovation (RD&I) clause of the Brazilian National Agency of Petroleum, Natural Gas, and Biofuels (ANP), which mandates the obligatory allocation of a percentage of gross production revenue to projects that encourage research and the adoption of new energy technologies. Shell Brasil is expected to invest between $60 million and $120 million in RD&I.

The pilot plant, set to be operational by 2025, will have an initial capacity of 10 MW, with potential expansion up to 100 MW in accordance with the unit's growth plan. Initially, electricity from the national grid will power the electrolysis plant, primarily producing renewable hydrogen. A portion of this hydrogen will be stored and subsequently dispatched to potential consumers. The remaining hydrogen will be directed to a renewable ammonia production plant.[100]

Porto do Açu, Casa dos Ventos, and Comerc Eficiência, an energy efficiency company within the Comerc Energia Group, signed a Memorandum of Understanding to develop green industrial projects based on hydrogen at the Porto do Açu complex. The agreement allows the companies to conduct feasibility studies for the installation of a hydrogen plant. Subject to study completion and licensing, the project encompasses the construction of a 2 GW green hydrogen plant across a 50-hectare area.[101]

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[98] Rosana Cavalcante de Oliveira R. (2022, August). Panorama do Hidrogênio no Brasil. IPEA.
[99] Rosana Cavalcante de Oliveira R. (2022, August). Panorama do Hidrogênio no Brasil. IPEA.
[100] Shell Brasil e Porto do Açu anunciam projeto inédito em hidrogênio verde. Porto do Açu. Retrieved from https://portodoacu.com.br/shell-brasil-e-porto-do-acu-anunciam-projeto-inedito-em-hidrogenio-verde/. Accessed on August 4, 2023.
[101] Porto do Açu assina acordo com Casa dos Ventos e Comerc Eficiência para planta de hidrogênio. Porto do Açu. Retrieved from https://portodoacu.com.br/porto-do-acu-assina-acordo-com-casa-dos-ventos-e-comerc-eficiencia-para-planta-de-hidrogenio/. Accessed on August 3, 2023.

Neoenergia and Prumo signed a Memorandum of Understanding (MoU) to conduct studies on green hydrogen production at Porto do Açu. The agreement also involves research on offshore wind generation in that coastal region, encompassing socio-economic and environmental aspects, supply chain, and logistics of the industrial and port complex.[102]

5.2 INVESTMENTS AND COOPERATION PER COUNTRY

In previous topics, hydrogen projects and investments in Brazil were identified, including several projects aimed at attracting investments in the hydrogen sector. Notably, there are projects underway or memorandums of understanding signed with companies from various countries, including Australia and Canada, at ports such as Pecém in Ceará, Suape in Pernambuco, and Açu in Rio de Janeiro.

Below is a consolidation of the prospective investments with their disclosed values by the country of origin in the hydrogen sector in Brazil:

Foreign investments in the sector[103]:

The country of origin of the resources	The prospective value (in US dollars)
Germany	39 million
Australia	15 billion
France	11 billion
The Netherlands	2 billion
Portugal	8 million

In addition to the partnerships established by companies, several agreements at the governmental and institutional levels have been identified. Below, we highlight some strong partnerships that have already been forged between Germany, the Netherlands, the European Union, and Brazil. These partnerships demonstrate the significance of Brazil globally when it comes to the energy transition.

[102] Neoenergia e Prumo assinam memorando para projetos de hidrogênio verde e eólica offshore no Porto do Açu. Porto do Açu. Retrieved from https://portodoacu.com.br/neoenergia-e-prumo-assinam-memorando-para-projetos-de-hidrogenio-verde-e-eolica-offshore-no-porto-do-acu/. Accessed on August 3, 2023.
[103] Rosana Cavalcante de Oliveira R. (2022, August). Panorama do Hidrogênio no Brasil. IPEA.

5.2.1 Germany

Minister of Mines and Energy, Alexandre Silveira, and the Federal Minister for Economy and Climate Action of Germany, Robert Habeck, signed on March 13th 2023, the document that reaffirms the **Brazil-Germany Energy Partnership**. This collaboration significantly contributes to the development of the energy sector in both countries, with the aim of strengthening energy security, promoting the energy transition, and reducing greenhouse gas emissions.

Among the actions planned by the cooperation is the establishment of a high-level steering committee, as well as 3 thematic working groups: "Renewable Energies," "Energy Efficiency," and "Green Hydrogen." The objective is to engage in a deep and continuous dialogue at the operational and technical levels to advance the implementation of measures derived from the Brazil-Germany Energy Partnership. The first meeting of the Steering Committee is expected to take place later this year to discuss the next steps and define concrete plans, along with the priorities to be addressed within the scope of bilateral energy cooperation – an essential topic for the economic, social, and environmental development of both countries.

Federal Minister for Economy and Climate Action of Germany, Robert Habeck, highlighted the country's initiative "H2 Global" and expressed interest in engaging Brazilian stakeholders in promoting the export of green hydrogen and derived products to Germany. Habeck emphasized Brazil's potential in generating renewable energies and expressed high expectations for the partnership between the two countries. Considering Brazil's enormous potentials, he believes that by the end of this decade, there will be a significant leap in these new energies, driven by increasingly powerful and productive equipment.

For this reason, Germany aims to scale up cooperation in energy generation with Brazil, seeking to achieve significant results in this field in the coming years. This objective is one of the key focuses of the energy partnership between Brazil and Germany.[104]

Another very active collaboration between Germany and Brazil is The **German-Brazilian Alliance for Green Hydrogen**. The German-Brazilian Alliance for Green Hydrogen was created in August 2020 by the Brazil-Germany Chambers in Rio de Janeiro and São Paulo to promote partnerships and business opportunities between Brazilian and German companies and institutions. Since then, it promotes different actions to boost the green hydrogen and PtX technologies development in Brazil, such as sector studies, events, workshops, Hackathons and the platform itself.[105]

Under the responsibility of the German-Brazilian Alliance for Green Hydrogen, a pioneering initiative has also been launched in Brazil by the Germans: an innovation call that will select enthusiasts, start-ups, and non-profit institutions presenting the best ideas to accelerate the economic and sectoral development of green hydrogen in Brazil. This program counts also on the support of the German Technical Cooperation Agency - GIZ (Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH) and the Ministry of Mines and Energy - MME.

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[104] Investimento alemão poderá alavancar projetos de hidrogênio de baixo carbono no Brasil. Ministério de Minas e Energia (MME). Retrieved from https://www.gov.br/mme/pt-br/assuntos/noticias/investimento-alemao-podera-alavancar-projetos-de-hidrogenio-de-baixo-carbono-no-brasil#:~:text=Not%C3%ADcias-,Investimento%20alem%C3%A3o%20poder%C3%A1%20alavancar%20projetos%20de%20hidrog%C3%AAnio%20de%20baixo%20carbono,efeito%20estufa%20nos%20dois%20pa%C3%ADses. Accessed on August 8, 2023.
[105] About us. (2023). H2 Verde Brasil. Retrieved from https://www.h2verdebrasil.com.br/en/about-us/

The proposals should cover one or more links in the green hydrogen (H2V) value chain: production (ideas for competitive H2V production and/or its derivatives - PtX), logistics (innovative ideas for the safe transport of H2V and PtX products), and application of green hydrogen (projects demonstrating the multiple uses of the product and its PtX in the Brazilian industry).[106]

5.2.2 The Netherlands

"We are making history for humanity. Our connection will bring the change the world needs for decarbonization." This statement was given by the governor of Ceará, Elmano de Freitas, on the 10th of May 2023 in São Gonçalo do Amarante during the signing of agreements for the creation of the **Green Hydrogen Corridor** between the Port of Pecém and the Port of Rotterdam, and the **Green Ports Partnership** between Ceará and the Netherlands. The ceremony was attended by the Prime Minister of the Kingdom of the Netherlands, Mark Rutte, along with other authorities and executives.

With this signing, the Pecém Complex and the Port of Rotterdam establish an end-to-end supply chain corridor for green hydrogen, including production at Pecém and reception and distribution at the Port of Rotterdam, to meet the demand in the Netherlands and other European countries. The following entities signed the creation of the corridor: Complexo Industrial e Portuário do Pecém, AES Brasil, Casa dos Ventos, Nexway, Havenbedrijf Rotterdam, Fortescue, and EDP.

The Prime Minister of the Netherlands also expressed his expectations regarding the cooperation. "Ports are the foundation of the Dutch economy, as well as of competitiveness worldwide. Traditionally, we have been seen as a gateway to Europe for various types of products. Rotterdam and Pecém can rightfully be called the gateway to hydrogen for Europe. Brazil is presented with an exceptional opportunity to strengthen its maritime sector. Brazil is also one of the leaders in commodity exports, and the total volume of cargoes is growing. So, this is a fantastic opportunity. The Netherlands, with its expertise in ports and logistics, is seeking to cooperate, and that's what we are already doing, and from today onwards, we will do much more together. Green hydrogen is not a technology of a distant future; it is of the present, happening right now. We are laying the foundation for the future in the green economy. Ceará is leading the way in Brazil, just as Rotterdam is a leader in Europe," emphasized Mark Rutte.[107]

During the World Hydrogen Summit 2023 our Dutch neighbours also signed **agreements** with some Brazilian states as for example with **the state of Rio Grande do Sul** and, of course, the **state of Ceará**. This partnership between Brazil and the Netherlands envisions signatories entering into agreements in line with the Sustainable Development Goals (SDGs), Promoting activities related to renewable energy production from onshore and offshore wind energy and green hydrogen (H2V) is among the key pillars of the memorandum of understanding. The collaboration aims to foster sustainable development and advance initiatives focused on these essential aspects of the energy transition.

[106] Title of the Article. (Year). H2 Verde Brasil. Retrieved from https://www.h2verdebrasil.com.br/noticia/alianca-brasil-alemanha-para-o-hidrogenio-verde-lanca-programa-de-inovacao/. Accessed on August 8, 2023
[107] Hub de Hidrogênio Verde: Governo do Ceará e Países Baixos firmam parceria para impulsionar produção e exportação. SEMA Ceará. Retrieved from https://www.sema.ce.gov.br/2023/05/10/hub-de-hidrogenio-verde-governo-do-ceara-e-paises-baixos-firmam-parceria-para-impulsionar-producao-e-exportacao/. Accessed on August 8, 2023.

The partnership also aims to support Dutch companies in increasing their exports, investing in the Brazilian maritime market, and encouraging domestic companies to expand their businesses in the European country. The exchange of knowledge and experiences related to port development and renewable energy will also be actively encouraged. This collaborative approach seeks to foster economic growth, facilitate technological advancements, and promote mutual benefits in the areas of trade, infrastructure, and renewable energy between Brazil and the Netherlands.[108]

5.2.3 European Union

The European Union will invest 2 billion euros in the production of green hydrogen in Brazil as part of the bloc's plans to reduce dependence on and use of fossil fuels.[109]

"Europe will invest 2 billion euros to support Brazilian green hydrogen production, promoting energy efficiency in its industry," said the President of the European Commission, Ursula von der Leyden, after a meeting with President Lula during her visit to Brazil in the first semester of 2023. "We, Europeans, have set a target to import 10 million tons per year of renewable hydrogen by 2030. We are interested in a reliable long-term partner. Let's work together on this," she added.

This funding is part of the **Global Gateway program**, an initiative launched by the European Union in 2021, aiming to raise 300 billion euros by 2027 to finance sustainable infrastructure projects in various countries. The investment in Brazil's green hydrogen production aligns with the EU's commitment to promoting renewable energy and combating climate change on a global scale.[110]

5.3 EXPORTS

The export of H2 can be seen as an opportunity if Brazil develops a coherent action plan to effectively compete with potential rivals. Countries such as Australia, Chile, Spain, Morocco, and Saudi Arabia, which also possess substantial potential for renewable energy generation, have already established their Green H2 development Action Plans (Roadmaps). They have adopted assertive stances in terms of promoting their potential and simplifying conditions to attract investors in green H2 plants, signaling possibilities of financing and incentive regulation.

Additionally, it's important to highlight that the European Union's strategy involves leveraging the development of the green hydrogen economy as a vector for economic recovery among its member countries in the post-COVID-19 pandemic period. Mechanisms are being devised in this direction, which could encourage the installation of electrolysis plants in these countries and the intra-block economic trade of green H2.

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[108] RS e Holanda firmam parceria para fomentar mercado de hidrogênio verde nos portos gaúchos. Governo do Estado do Rio Grande do Sul. Retrieved from https://www.estado.rs.gov.br/rs-e-holanda-firmam-parceria-para-fomentar-mercado-de-hidrogenio-verde-nos-portos-gauchos. Accessed on August 9, 2023.

[109] União Europeia vai investir R$ 10 bi em hidrogênio verde no Brasil. Exame. Retrieved from https://exame.com/esg/uniao-europeia-vai-investir-r-10-bi-em-hidrogenio-verde-no-brasil/ Accessed on August 9, 2023.

[110] Produção de hidrogênio verde no Brasil deve viver salto após investimentos de R$ 10 bilhões prometidos pela União Europeia Petronotícias. Retrieved from https://petronoticias.com.br/producao-de-hidrogenio-verde-no-brasil-deve-viver-salto-apos-investimentos-de-r-10-bilhoes-prometidos-pela-uniao-europeia/. Accessed on August 9, 2023.

This underscores the cost of renewable energy generation as a pivotal factor for H2V competitiveness, alongside the presence of a mature logistics sector geared toward the international market.

International cooperation remains a strategic advantage for bolstering H2 in the global market. Thus, considering national advantages such as the availability of competitively priced renewable resources and an advanced domestic industry, countries demanding H2V or sharing similar interests with Brazil could form essential partnerships for H2 implementation on a national scale. Just like Germany and the Netherlands that have formed partnerships with several countries, including Brazil, to develop cooperative activities, aiming to purchase green hydrogen and also sell products developed by its industry.

Brazil's positioning in the international H2 market is also viewed as a strategic advantage from the perspective of the associations. They emphasize the rapid growth of this market and Brazil's potential to emerge as a major H2 supplier, which could significantly impact the export sector and the overall economy through job generation prospects.

Lastly, well-developed logistics play a central role in identifying the export-oriented development of the H2 economy via ports. Notably, initiatives for establishing green H2 hubs at the Port of Pecém and the Port of Açu were already highlighted in this study. These hubs have shareholders such as the ports of Rotterdam and Antwerp-Bruges, respectively and this can play a crucial role in the development of green H2 exports.

This opportunity is closely linked, therefore, to the capability of transporting hydrogen over long distances at efficient costs. As an illustration, the nautical distances from potential exporters to the Port of Antwerp-Bruges are indicated in following table:

Port	Nautical miles
Australia (Newcastle)	11630 via Suez Canal
Chile (Valparaíso)	7460 via Panama Canal
Brasil (Fortaleza)	4021
Brasil (Rio de Janeiro)	5248

Source: based on sea-distances.org, 2023

It can be observed that Brazil, particularly with its Northeastern ports, is closer to the European market than Australia and Chile are.

In this context, Brazil could potentially supply around 40% of Europe's electricity (import) demand if 100% of the anticipated production from future offshore wind farms is directed towards export, utilizing green hydrogen as a storage medium.

This projection was presented by the lead researcher of the Sustainability Laboratory at the SENAI Institute for Innovation in Renewable Energies (ISI-ER), Juan Ruiz, during the event "Fórum Nacional Eólico – Carta dos Ventos" in 2022.

During the presentation, the ISI-ER researcher explained that, with the offshore production potential projected by the Energy Research Company (EPE), Brazil would have a surplus of 5,040 Terawatt-hours (TWh) of energy for export, which would represent 1,764 TWh available for use at the final destination – such as the European market.

For comparison, Europe's energy import in 2020 was estimated at 4,000 Terawatt-hours. "Out of these 4,000 TWh, 38% were supplied by Russia, which is currently in conflict (with Ukraine), and it's gray energy," Ruiz explained, referring to Russia's supply of input based on fossil fuels, in contrast to what Brazil would offer, originating from sources like wind energy.

The scenario proposed by him takes into account Energy Research Company's (EPE) projections for electricity demand in Brazil until 2026, the nationally estimated total offshore potential of 700 Gigawatts, and anticipated energy losses at various stages of production and export, such as electrolysis, compression, and transportation to target markets.[111]

[111] Com eólicas offshore e H2 verde, Brasil conseguiria suprir 40% da energia importada pela Europa, diz ISI-ER. FIERN - Federação das Indústrias do Estado do Rio Grande do Norte. Retrieved from https://www.fiern.org.br/com-eolicas-offshore-e-h2-verde-brasil-conseguiria-suprir-40-da-demanda-de-energia-importada-pela-europa-diz-isi-er/. Accessed on August 9, 2023.

6. CONCLUSION

In conclusion, the hydrogen market in Brazil finds itself at a crucial crossroads, presenting a complex panorama that evokes both anticipation and prudence. The prevalent deployment of grey hydrogen, though serving as an initial stride towards energy diversification, serves to accentuate the pressing requirement for a transition to more ecologically viable alternatives. Nonetheless, the substantial promise held by green hydrogen should not be underestimated. Boasting the potential for carbon-neutrality and harnessing Brazil's profusion of renewable resources, it emerges as a captivating prospect capable of reshaping the energy landscape and realizing ambitious climate objectives. It is important to recognize that the existing utilization of grey hydrogen can serve as a stepping stone towards the eventual widespread adoption of green hydrogen, facilitating a gradual yet purposeful transformation in the country's energy paradigm.

The ongoing network of research and development within the country signifies a commitment to innovation, fostering the growth of hydrogen technologies and their integration into various sectors. This collaborative approach not only promotes technological advancement but also enhances Brazil's global competitiveness in the emerging hydrogen economy.

At the forefront of this evolving landscape, several major companies have already recognized the potential benefits of hydrogen adoption and have initiated projects and investments. Their involvement demonstrates the private sector's readiness to embrace transformative energy solutions, further solidifying Brazil's position in the global hydrogen arena.

The potential of partnerships with Brazil for the production of green hydrogen stands as a beacon of opportunity in the global pursuit of sustainable energy solutions. As exemplified by successful collaborations such as the German and Dutch initiatives, these partnerships have the power to reshape the energy landscape, foster technological innovation, and drive significant progress towards decarbonization.

The collaborative efforts between Brazil, Germany, and the Netherlands underscore the effectiveness of shared expertise and resources in advancing green hydrogen production. Memoranda of Understanding (MOUs) in place symbolize the commitment of these nations to jointly develop and scale up hydrogen technologies, leveraging their respective strengths to accelerate the transition to a low-carbon future.

The German-Brazilian collaboration, for instance, capitalizes on Brazil's abundant renewable resources and Germany's technological prowess to tap into the vast potential of green hydrogen. This partnership not only enhances energy security but also promotes sustainable economic growth, positioning both nations at the forefront of the emerging hydrogen economy.

Similarly, the Dutch-Brazilian partnership signifies a united effort to explore innovative pathways for green hydrogen production, storage, and utilization. By sharing knowledge and experience, these nations create a synergy that not only benefits their domestic energy landscapes but also contributes to the global fight against climate change.

These examples highlight the significance of international cooperation in addressing complex challenges such as sustainable energy transition. As Brazil's immense renewable energy potential converges with the technological capabilities of its partners, the stage is set for transformative change in the way energy is produced and consumed.

Flanders, armed with its knowledge, experience, and the ambition to become a hydrogen hub, has the chance to lead by example. By following in the footsteps of Germany and the Netherlands, and embracing collaboration as the driving force, Flanders and Brazil can collectively pave the way for a greener, more sustainable energy future that transcends borders and benefits all of humanity.

However, amid this wave of enthusiasm and progress, a critical hurdle remains the lack of a comprehensive legal framework. The absence of clear regulations hampers the growth of the hydrogen market, creating uncertainty for investors and hindering the market's full potential. To fully capitalize on the opportunities presented by hydrogen, it is imperative for Brazilian policymakers to swiftly establish a stable regulatory environment that incentivizes investment, supports innovation, and ensures the sustainable development of the hydrogen sector.

In essence, the hydrogen market in Brazil embodies a blend of existing infrastructure and untapped potential, marked by the dominance of grey hydrogen but driven by the prospects of green hydrogen. The interconnectedness of research and industry efforts showcases a nation poised to lead in hydrogen technology. However, to truly unlock the benefits and align with global sustainability goals, Brazil must expedite the creation of a robust legal framework and roadmap, thereby fostering a conducive environment for the hydrogen market to flourish, bringing about a new era of energy and environmental progress.

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