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BRAZILIAN CENTER FOR INTERNATIONAL RELATIONS

ENERGY PROGRAM

HYDROGEN AND ENERGY TRANSITION: OPPORTUNITIES FOR BRAZIL

May, 2022

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ENERGY PROGRAM

The Program focuses on the future of energy and global energy trends and seeks out solutions to create a competitive and attractive investment environment for Brazil.

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Jorge Camargo

Vice-Chairman of the Board of Trustees of CEBRI and coordinator of the Energy Program. He is a member of the Boards of Directors of the Ultrapar and Prumo Global Logistics Groups. He was Chair of the Brazilian Institute of Petroleum, Gas and Biofuels (IBP) and is today an emeritus member of its Board of Directors. He has held executive positions at Petrobras, including as a member of the Executive Board, responsible for the International Area, and at Equinor, initially as Senior Vice President, at the company's headquarters in Norway, then as Chair of Equinor in Brazil.

SENIOR FELLOW

Rafaela Guedes

Rafaela Guedes is Petrobras' Chief Corporate Social Responsibility Officer. In this role, she is responsible for working with communities to co create solutions transforming positively the regions where the company operates, anticipating and managing social and environmental impacts of current and future activities. In addition, she seeks to ensure respect for human rights and to promote of diversity. She is currently member of the Oil and Gas Climate Initiative Executive Committee.

SENIOR RESEARCHER

Gregório Araújo

Gregório Araújo has served in the position of Senior Economist at Petrobras since 2008, with management roles in the Strategy and Planning department. Araújo served as Member of the "Future Energy Leaders Program" and of the "Scenarios Committee" of the World Energy Council, as well as Secondee at the International Energy Agency, contributing to the elaboration of the Brazil chapter at the World Economic Outlook's 2013 edition.

BRAZILIAN CENTER FOR INTERNATIONAL RELATIONS
Rua Marquês de São Vicente, 336 – Gávea
Rio de Janeiro / RJ - 22451-044
Tel + 55 21 2206-4400 - cebri@cebri.org.br
www.cebri.org

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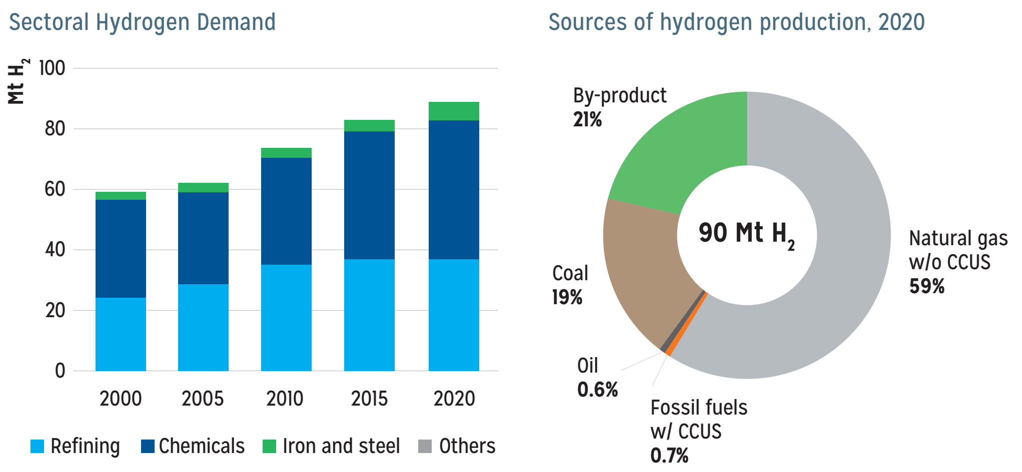
Background

The global hydrogen (H2) market was estimated at around US$ 190 billion in 2020, reaching a volume of approximately 90 million tonnes (Mt), 50% more than in 2000 (IEA, 2019 and 2021). Of this total, 72 Mt (80%) are produced by plants dedicated to hydrogen production, obtained almost entirely from fossil fuels (including 60% from natural gas and 19% from coal); and 18 Mt (20%) are a byproduct of plants designed primarily for other products.

Looking at it from the demand side, 72 Mt are consumed as pure hydrogen and 18 Mt are used in mixtures with other gases to produce methanol and steel through the direct reduction of iron (DRI). Regardless of how hydrogen is used, almost all consumption occurs in oil refineries and industrial uses. Oil refineries account for around 40 Mt. They use hydrogen for fuel quality specifications in hydrotreating and hydrocracking units. The chemical industry uses another 45 Mt, with almost 75% intended for ammonia production. Steel production accounts for the remaining 5 Mt. This sectoral distribution has remained basically stable over the last 20 years (IEA, 2021).

Despite the current scenario, hydrogen has an important versatility in the context of transition to a low-carbon economy. It can be used directly as a low or zero-carbon energy source (depending on its production process, whether from capture or renewable sources)

FIGURE 1 - GLOBAL HYDROGEN MARKET: SUPPLY AND DEMAND



Source: IEA, 2021

in sectors that are difficult to decarbonize or in energy storage, enabling a larger share of intermittent renewables, such as wind and solar power.

Since the mid-20th Century, moments of global enthusiasm for the widespread use of hydrogen as an energy source have been observed, but they were not translated into productive capacity. Nevertheless, some factors indicate that a stage of robust growth may be incipient to enable conditions for a hydrogen economy: i) reduction in the cost of renewables for low-carbon hydrogen production; ii) the favorable stance of several governments and major industrial players regarding the hydrogen economy, iii) technological progress with positive impacts on the competitiveness of hydrogen, indicating that hydrogen may reach a significant percentage of low-carbon energy in the future (E+ TRANSIÇÃO ENERGÉTICA, 2021).

In fact, hydrogen is increasingly considered essential for achieving a broad decarbonization of economies. It can promote the coupling of fuel, electrical and industrial markets, so that the cost reduction of generating renewable energy can also impact sectors in which electrification is difficult.

In this regard, the Norwegian Consulate, in partnership with CEBRI, promoted, on September 29, 2021, a panel discussion on the perspectives, technical challenges and economic feasibility of hydrogen production projects, as well as alternative national development strategies for this technology and its potential advantages for Brazil as a relevant actor in a hydrogen-based economy. In addition to the participation of the General Consul of Norway, Mariane Fosland, and the CEBRI Trustee, Winston Fritsch, the panel heard the following talks:

- *"Rising to the challenge of a hydrogen economy"* by Jørg Aarnes, Global Lead on Low Carbon Energy Systems at DNV.
- *"Water Electrolyzers for Applications of Green Hydrogen"* by Tom Skoczylas, Regional Sales Manager at NEL Hydrogen.
- *"Green Hydrogen: Brazil Advantages"* by Marcus Silva, Commercial Director for Brazil and Argentina at Air Products.
- *"Opportunities for a Low Carbon Hydrogen Economy in Brazil"* by Giovani Machado, Director for Energy Economics and Environmental Studies at EPE.
- *"Solutions for Hydrogen Production & Purification"* by Daniel Lopes, Commercial Director at Hytron.

Presentations are available on the CEBRI website: Hydrogen and Energy Transition: Opportunities for Brazil.

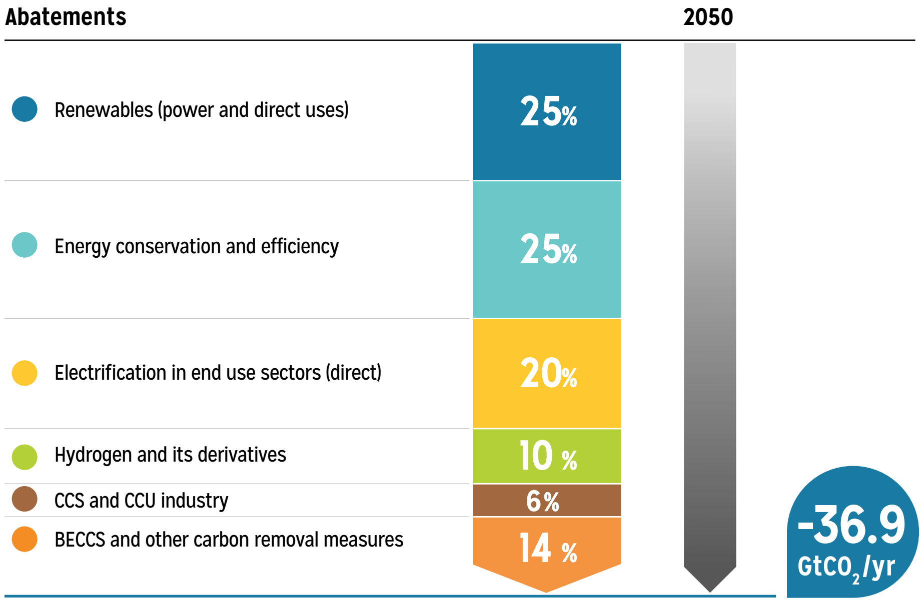
Hydrogen: an essential element for carbon neutrality

After decades of being considered a disruptive energy source with great potential for the future, but with considerable market and technological challenges, hydrogen has become a strategic goal of governments (and even businesses) all over the world. Currently, hydrogen roadmaps have been submitted by 18 countries (HYDROGEN COUNCIL, 2020). More than 20 governments have publicly announced that they are seeking to develop strategies to promote hydrogen in their economies and there are many companies researching business opportunities in the hydrogen economy (IEA, 2021).

The hydrogen market is expected to gain traction from post-pandemic energy policies geared to economic stimulus and accelerating energy transition in several countries. According to a study carried out by the International Energy Agency (IEA, 2021b), *Net Zero by 2050: A Roadmap for the Global Energy Sector*, it will be necessary to promote the use of hydrogen for different areas of a carbon neutral energy system, so that it will represent 10% of the total final energy consumption in 2050.

Likewise, the International Renewable Energy Agency (IRENA) predicts that H2 will account for about 12% of the final energy consumption by 2050. Two thirds of this production will be green hydrogen, generated from renewable electricity, requiring about 5,000 GW in electrolysis capacity. The remaining amount will be produced from natural gas with carbon capture (blue hydrogen). Considering a scenario in which the temperature increase is restricted to 1.5oC, around 10% of the required reduction is due to the use of low-emission H2 (IRENA, 2020).

FIGURE 2 - CARBON EMISSIONS ABATEMENTS FOR THE 1.5OC SCENARIO



Source: IRENA, 2021

Other scenarios ratify that hydrogen is the energy carrier which will allow meeting the temperature control commitments made under the Paris Agreement. For instance, DNV's *Energy Transition Outlook* estimates that in the current most probable future scenarios for energy transition, the Paris Agreement targets will not be achieved and that, possibly, the 1.5°C threshold will be reached in the next decade and that of 2.0°C around 2053. In these scenarios, hydrogen represents only 5% of the final energy consumption in 2050 and only in the following decade would it begin to show a consistent increase in demand.

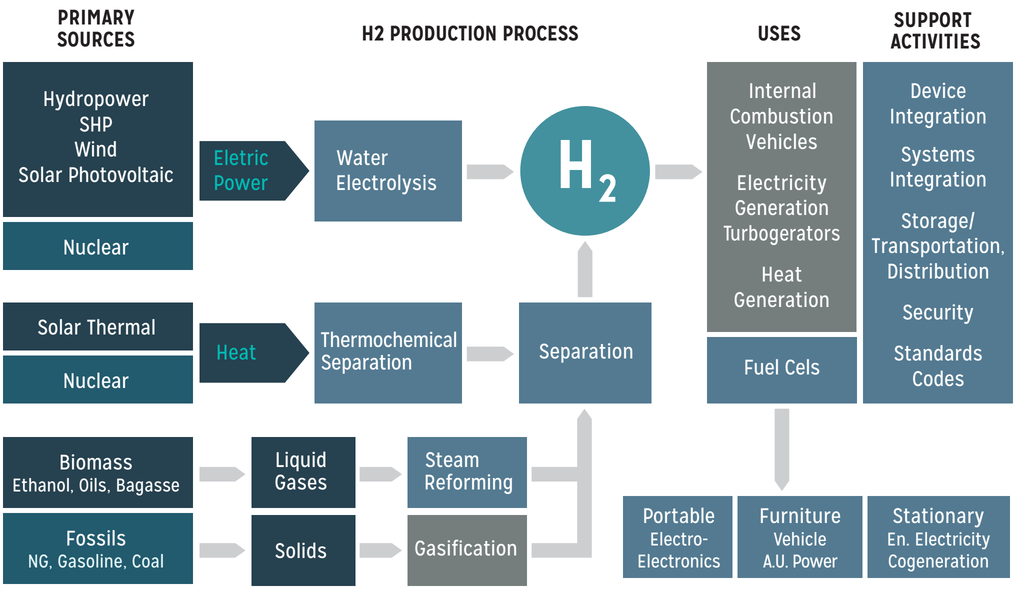
The DNV study confirms that H_2 will have an important role in decarbonizing the global economy in the long run but calls attention to the need for concrete actions to begin this decade to enable meeting the Paris Agreement targets. Thus, some initiatives, such as the addition of H2 to the natural gas pipelines, are being put forward to assist the distribution to accelerate the process of developing the hydrogen supply chain, facilitate the participation of intermittent renewables, and assist in the decarbonization of the industrial sector.

Despite these initiatives, there are several technological, energy and economic challenges throughout the hydrogen value chain that must be overcome to promote the production of low-carbon hydrogen that is both competitive and suitable for a fair energy transition.

One of the major technical hurdles preventing the wider energy use of hydrogen is its transport. Technological solutions provide three alternatives for distributing it to consumption centers: in gaseous state (compressed or through pipelines), liquefied, or through a carrier, such as ammonia or methanol. It is expected that in the markets in which there is greater development in the use of hydrogen for final consumption, it will be mixed with natural gas transported in gas pipelines and that, in the future, a network of pipelines will be adapted or developed specifically for hydrogen. For long distance transportation, including international trade, ammonia is a promising method, requiring downstream investments to extract pure hydrogen at the destination.

Another important challenge is the emissions resulting from hydrogen production. Today, the most widely used process for producing hydrogen is natural gas reforming or partial oxidation of fossil fuels such as coal. This process generates large amounts of carbon dioxide, around 10 tCO_2/tH_2 in natural gas reforming and 12-19 tCO_2/tH_2 during partial oxidation of coal (IEA, 2019).

FIGURE 3 - POSSIBLE PATHWAYS FOR HYDROGEN PRODUCTION AND USE



Source: CGEE, 2010

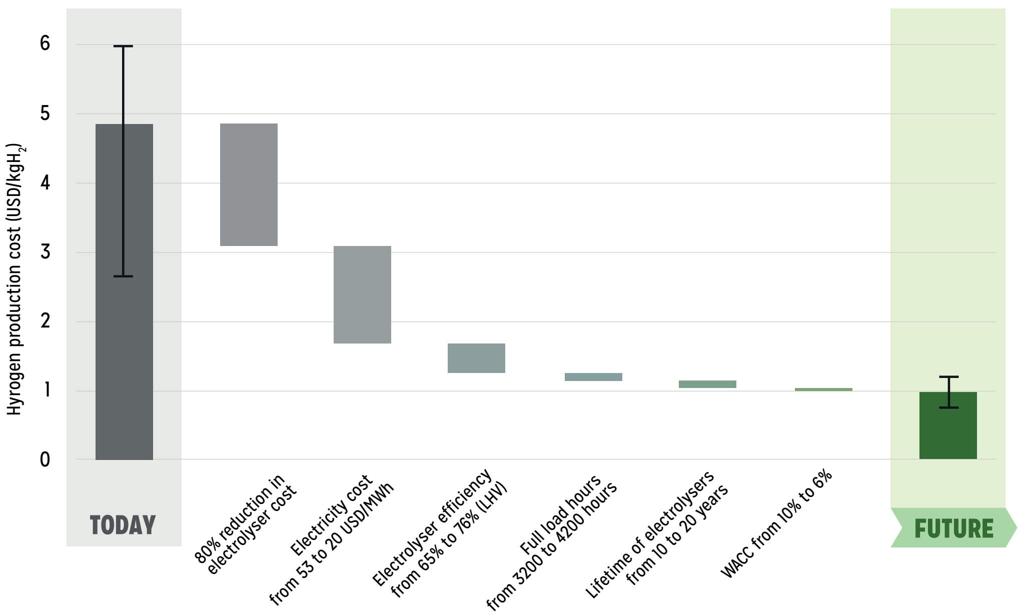
For H_2 to be able to contribute to decarbonization, processes and energy sources must be developed that allow its production without CO_2 emissions, which has led to a series of proposals and classifications according to the raw material/process used to obtain H_2. The types of hydrogen with a lower carbon footprint usually seen are blue hydrogen (obtained by catalytic reforming of natural gas with carbon capture) and green hydrogen (obtained by electrolysis of water using electricity from renewable sources).

FIGURE 4 - CLASSIFICAÇÃO DO H_2 DE ACORDO COM A MATÉRIA-PRIMA E PROCESSO PRODUTIVO

Another crucial element is competitiveness in the production of low-carbon hydrogen. In fact, the drop in costs of generating green hydrogen is one of the most significant factors in the definition of the speed and size of its potential market. The advance of technology and economies of scale are essential to reduce the costs of electrolyzers and of generating renewable electricity, the main components for green hydrogen competitiveness.

Reductions in the cost of electricity and electrolyzers together with increased efficiency and operational lifetime could lead to an 80% reduction in the cost of green hydrogen, making it competitive for several applications in the future.

FIGURE 5 - DETERMINING FACTORS FOR REDUCING THE COSTS OF GREEN HYDROGEN

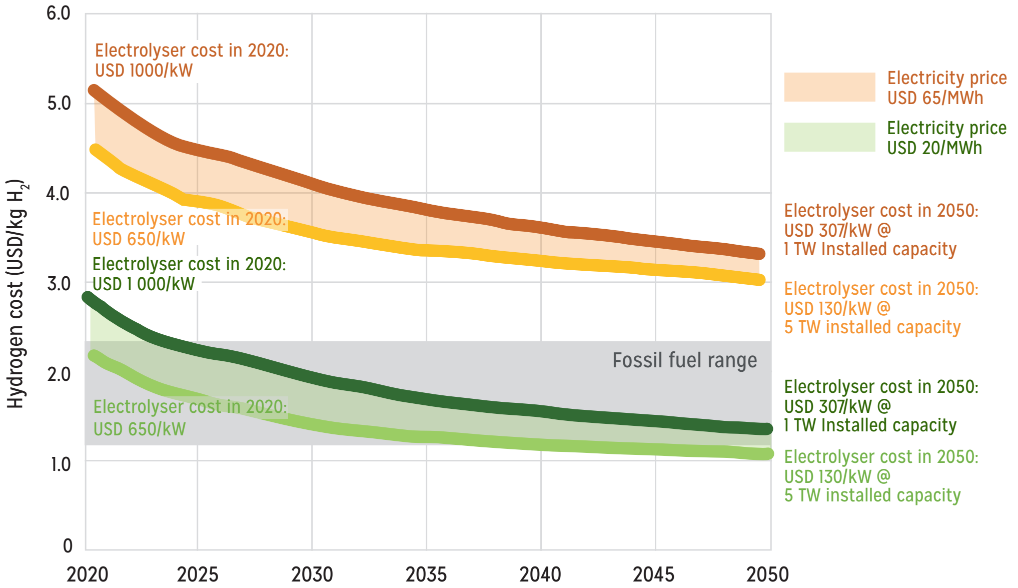


Note: 'Today' captures best and average conditions. 'Average' signifies an investment of USD 770/kilowatt (kW), efficiency of 65% (lower heating value – LHV), an electricity price of USD 53/MWh, full load hours of 3200 (onshore wind), and a weighted average cost of capital (WACC) of 10% (relatively high risk). 'Best' signifies investment of USD 130/kW, efficiency of 76% (LHV), electricity price of USD 20/MWh, full load hours of 4200 (onshore wind), and a WACC of 6% (similar to renewable electricity today).

Source: IRENA, 2020

Understanding long-term cost projection is as important as estimating the rate at which these costs will drop. The graphs of Figure 6 show that countries that can produce renewable energy at around 20 US$/kW will be capable of generating green hydrogen with costs like those of fossil hydrogen, as soon as this decade.

FIGURE 6 - PATH OF COST REDUCTION OF GREEN HYDROGEN AS A FUNCTION OF ELECTRICITY PRICE AND THE CAPEX OF ELECTROLYZERS



Note: Efficiency at nominal capacity is 65%, with a LHV of 51.2 kilowatt hour/kilogramme of hydrogen (kWh/kg H2) in 2020 and 76% (at an LHV of 43.8 kWh/kg H2) in 2050, a discount rate of 8% and a stack lifetime of 80 000 hours. The electrolyser investment cost for 2020 is USD 650-1000/kW. Electrolyser costs reach USD 130-307/kW as a result of 1-5 TW of capacity deployed by 2050.

Source: IRENA, 2020

In this context, 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 most generates 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.

In addition, having a transport system that connects most of the country 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.

A recent McKinsey survey (2021) confirms Brazil's competitive position. According to this study, the levelized cost of Brazilian green hydrogen (LCOH) would hover around 1.50 US$/kg H_2 in 2030 and 1.25 US$/kg H_2 in 2040, comparable to the best locations in the USA, Australia, Spain and Saudi Arabia. The study also shows that in the 2030 scenario, projects outside the grid will probably have an LCOH around 10% higher than those of projects connected to the grid, with the best locations in the Southeast being slightly more competitive than those in the Northeast, using the current grid tariff configuration.

In addition to electricity being the main factor in the cost of hydrogen production, an issue addressed to a great extent in the Brazilian scenario, it is also necessary to focus on cost reduction and efficiency increase of electrolyzers to allow the country to incorporate green hydrogen electricity.

FIGURE 7 - TABELA COMPARATIVA ENTRE AS PRINCIPAIS TECNOLOGIAS PARA PRODUÇÃO DE H_2 VERDE DE ELETROLISE

	2020				2050			
	Alkaline	PEM	AEM	SOEC	Alkaline	PEM	AEM	SOEC
Cell pressure [bara]	< 30	< 70	< 35	< 10	> 70	> 70	> 70	> 20
Efficiency (system) [kWh/KgH_2]	50-78	50-83	57-69	45-55	< 45	< 45	< 45	< 40
Lifetime [thousand hours]	60	50-80	> 5	< 20	100	100-120	100	80
Capital costs estimate for large stacks (stack-only > 1 MW) [USD/kW_{el}]	270	400	-	> 2 000	< 100	< 100	< 100	< 200
Capital cost range estimate for the entire system > 10 MW [USD/kW_{el}]	500-1000	700-1400	-	-	< 200	< 200	< 200	< 300

Note: PEM = Polymer Electrolyte Membrane (commercial technology); AEM = Anion Exchange Membrane (lab-scale today); SOEC = Solid Oxide Electrolysers (lab-scale today).

Source: IRENA, 2020

There are currently several technologies being studied for generating H_2 through electrolysis, as shown in Figure 7. Each of these has advantages and disadvantages and when they mature, it is expected that they will compete among themselves. Currently the Alkaline and PEM technologies have higher maturity levels and are the main technologies available for the development of projects on a larger scale.

A Hydrogen Economy in Brazil

The McKinsey survey (2021) estimates a potential hydrogen market in Brazil at around of 15-20 billion dollars in 2040, with most of this potential (US$ 10-12 billion) for the domestic market, particularly cargo transport by trucks, steel industry and other industrial energy uses. Another US$ 4-6 billion would arise from exports of green hydrogen products to Europe and the US.

There is naturally great uncertainty regarding the realization of this accelerated scenario for developing a hydrogen economy in Brazil. In addition to technical hurdles, some of which have already been mentioned, a National Plan must be developed that encompasses long-term vision, national strategies, and a roadmap of actions, with special reference to regulatory and institutional arrangements and incentive policies that will provide the US$ 200 billion in investments required to realize that scenario, including the 180 GW of additional renewable electricity capacity.

We must emphasize that Brazil has shown interest in development of hydrogen at least since 1975, with activities such as the creation of the Hydrogen Laboratory (LH2). In 1995, the Ministry of Science, Technology, and Innovation (MCTI) began its activities in Hydrogen Energy and one of the first major milestones was the implementation of the National Reference Center for Hydrogen Energy (CENEH), in 1998. In 2002, the Ministry published the Brazilian Fuel Cells Program (ProCaC), whose aim was to "organize and promote research and technological development through projects in research institutions together with private companies". ProCaC involved companies and universities and in 2005, it underwent reformulation receiving the name "Science, Technology and Innovation Program for the Hydrogen Economy" (ProH2).

In 2003, Brazil became a member of the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE1), which aims to exchange government, industrial and academic information on fuel cells and on hydrogen in society.

Two years later, the "*Roadmap for Structuring the Hydrogen Economy in Brazil*" (MME, 2005) was published, with targets for 20 years highlighting: i) the importance of the various technological paths in which Brazil could have a competitive edge; ii) the role of natural gas in the transition, until green hydrogen is predominant; and iii) the expansion to distributed generation markets, isolated regions and urban buses.

In 2010, the study "*Energy Hydrogen in Brazil: Input for Competitiveness Policies: 2010-2025*" (CGEE, 2010) put forward recommendations for incentives for the hydrogen economy, with the inclusion of Ministries (Science, Technology and Innovation, Mines and Energy, and Environment), government agencies (Brazilian Electricity Regulatory Agency, National Council for Scientific and Technological Development, Funding Authority for Studies and Projects, Brazilian Development Bank and National Institute for Metrology, Standardization and Quality) and research institutions (Center for Energy Research, Telecommunications Research and Development Center, National Institute of Technology and Institute of Technology for Development) for short-term (0-5 years), medium-term (5-10 years) and long-term (10-15 years) actions.

The creation of the Brazilian Hydrogen Association (ABH2), in 2017, was an initiative to better organize the actions and resources (public and private) that has generated good results in joint action with MCTI, MEC, MME, ANEEL, ANP and Eletrobras and other federal bodies.

In 2020, the 2050 National Energy Plan (PNE, 2050) indicated that hydrogen was a disruptive technology as well as an interesting element in the context of decarbonizing the energy supply mix, and listed several uses and applications, as well as including recommendations for energy policies.

In 2021, EPE published "*Basis for the Consolidation of the Brazilian Hydrogen Strategy*", addressing the market environment, technological pathways, costs, challenges, the role of hydrogen in energy transition and, lastly, the implications for public policies.

The MME also produced "Mapping of the Brazilian Hydrogen Sector: Current and Potential Outlook for Green Hydrogen", which provided a panorama of the industry and key academic and institutional players active in the area in Brazil, as well as an overview of the main technologies for employing hydrogen.

In 2021, CNPE issued two resolutions with positive implications for hydrogen development. The first, CNPE Resolution No. 2/2021, provides the priorities for allocation of research, development and innovation resources regulated by the Brazilian Electricity Regulatory Agency (ANEEL) and by the Brazilian Agency for Oil, Natural Gas and Biofuel (ANP) to hydrogen, among other issues related to the energy sector and energy transition. The second, CNPE Resolution No. 6/2021, deals with a proposal for guidelines for the National Hydrogen Program (PNH2).

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 has favorable characteristics for the production of green hydrogen. It has a potential for solar and 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 eight days away from the Rotterdam Port.

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.

Despite these initiatives, Brazil still needs to further develop a detailed national strategy for the use of its full potential for developing a hydrogen economy. As mentioned above, Brazil is one of the most competitive markets for wind and solar power, attracting several national and international investors, and still has an unexplored potential. Brazil also has other sources, which make its situation unique. According to E+ TRANSIÇÃO ENERGÉTICA (2021), Brazil stands out with its pilot-scale development of technologies for reforming ethanol, biogas, and glycerol as well as for generating hydrogen from the fermentation of agro-industrial wastes.

The National Hydrogen Program (PNH2) was established to engage the public and private sectors, as well as academia and international partners, to develop a broad and competitive hydrogen market.

The Program has six main pillars, as shown in Figure 8.

FIGURE 8 - PILLARS OF THE NATIONAL HYDROGEN PROGRAM

Source: PNH2

With respect to the international cooperation provided for in Axis 6 of the PNH2, some proposed guidelines were:

a. **Map and compile** the treatment given to hydrogen in energy planning and in the corresponding sector policies of the key countries and international actors in the hydrogen sector.

b. **Develop and enhance** international dialog and cooperation – at the bilateral, regional, and multilateral levels – in the area of hydrogen, with a flexible and universal approach in terms of partners and contacts – governments, international organizations, and specialized agencies – and of the adopted technological paths.

c. **Encourage and facilitate** industrial and productive partnerships along the hydrogen chain, with emphasis both on attracting investments and on inserting Brazil into global value chains, according to national interests and competitive edges.

d. **Participate**, in a sovereign manner, in international discussions related to the definition of the hydrogen production and use chain, as well as to the conformation of the global hydrogen market (taxonomies and ESG criteria, certifications, standards, among others), with a view to the international competitiveness of the Brazilian hydrogen sector along its various paths.

e. **Identify** international funding sources and instruments, such as "green" funds, international cooperation agencies, multilateral development banks and investment funds, as well as "blended finance" instruments, to support and execute projects related to the production and use of hydrogen in Brazil.

f. **Foster** exchange among Brazilian and international institutions and centers dedicated to research, development, and technological innovation in the hydrogen sector.

Opportunities for Brazil — Norway Collaboration

Regardless of the production path, the challenges for creating the entire infrastructure for the hydrogen economy are enormous. They are global challenges, too large to be addressed only by a few companies or even a few countries. In this regard, a broad engagement and collaboration between governments and market agents is essential for the success of the hydrogen economy.

Another important aspect is the processes for certification of clean hydrogen. Criteria should be agreed on and recognized internationally. Brazil has moved forward in this direction with its Renovabio program but given the complexity and diversity of sources for hydrogen production, this is an issue that needs further development. An example is the fertilizer manufacturer Yara, which has contracted the supply of biomethane to produce ammonia. This ammonia, once the origin of its raw material has been certified, may be commercialized as green ammonia, making it competitive in markets that already begin to tax the carbon content in the value chain of the traded products.

Brazil and Norway have several characteristics in common, such as very clean energy supply mixes, experience in generation of renewable energy, oil and natural gas, and major naval and industrial sectors. These characteristics generate an important foundation for the creation of a hydrogen market.

Norway, like Brazil, is actively involved in several international initiatives to develop the hydrogen economy. Furthermore, they have a long tradition of cooperation in the energy sector, which could be expanded to include the development of the hydrogen economy.

Three aspects bring Brazil and Norway closer to the development of a hydrogen economy:

- Both countries have enormous hydropower generation that could lead both countries to spearhead the production of green H2/NH3.
- Norway leads the race for the development of low-carbon vessels, such as those powered by batteries, hydrogen, and ammonia.
- Norway has also led efforts in CCS. Cooperation among Norway and Brazil could lead the latter to a prominent position in the production of ammonia and blue hydrogen.

Final Considerations

Bearing in mind the recognition of the significant role that the production and use of hydrogen can play towards net carbon neutral emissions and that Brazil has a major potential in diversified energy resources, it has all the conditions to stand out in this market.

Since the challenges for developing the hydrogen economy are enormous, it is important that Brazil build a long-term vision, with national strategies and a roadmap of actions that aim to develop regulatory and institutional arrangements and incentive policies that enable the required investments. Equally important is cooperation with other countries that are further advanced in realizing a hydrogen economy to develop shortcuts to promote technical and regulatory progress to accelerate the consolidation of this energy carrier.

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Rua Marquês de São Vicente, 336
Gávea, Rio de Janeiro – RJ - Brasil
22451-044

Tel: +55 (21) 2206-4400

cebri@cebri.org.br

@cebrionline **cebri.org**