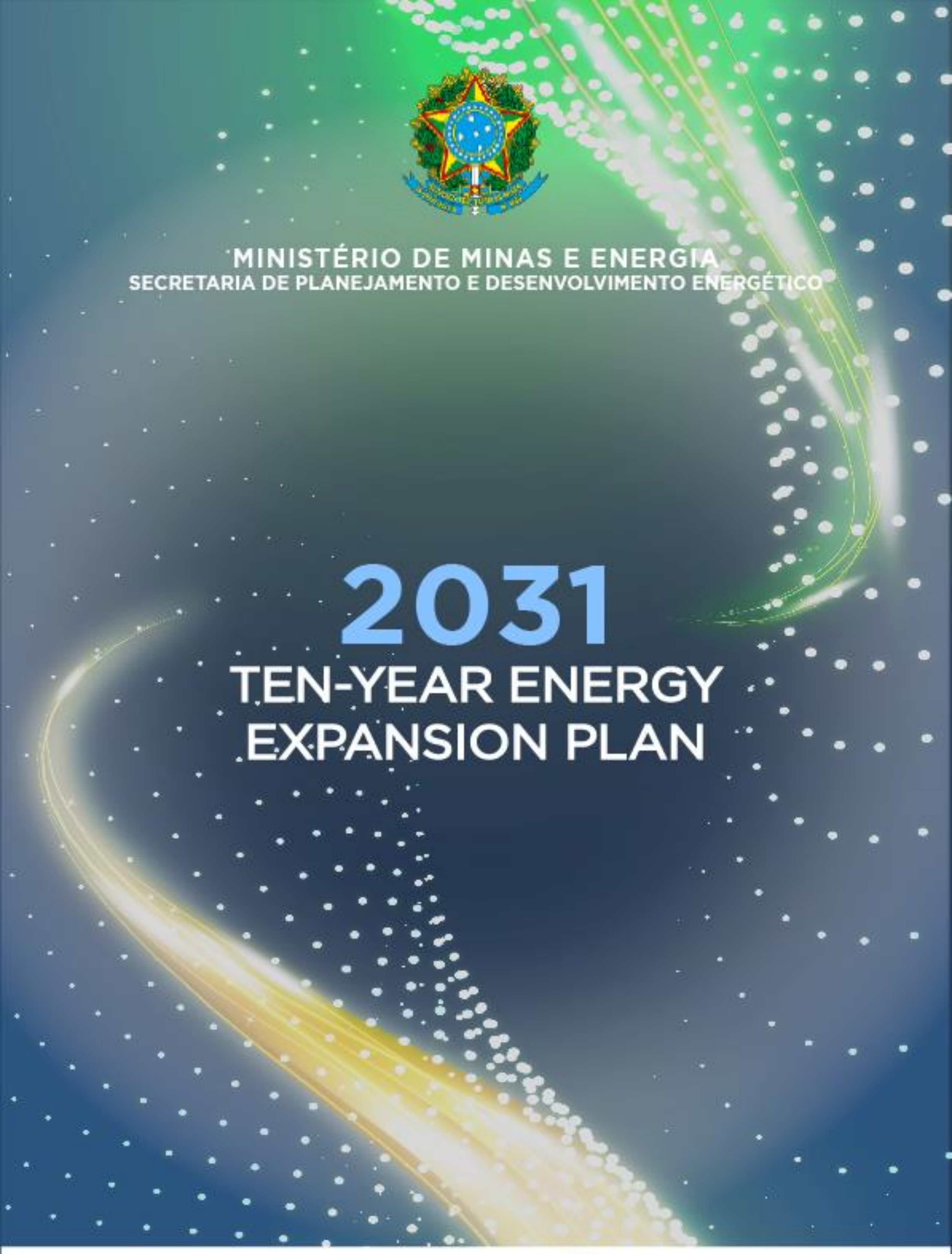

MINISTÉRIO DE MINAS E ENERGIA
SECRETARIA DE PLANEJAMENTO E DESENVOLVIMENTO ENERGÉTICO

2031
TEN-YEAR ENERGY EXPANSION PLAN

epe
Empresa de Pesquisa Energética

Ministério de
Minas e Energia

12. Hydrogen

Hydrogen has gained greater relevance in the energy and climate strategy of several countries, including Brazil, mainly because it offers an alternative for sectors that are difficult to reduce carbon emissions and because it also constitutes an energy vector, enabling its storage, and favoring the coupling of the energy sector to the industry and transportion sectors. In light-duty vehicles, hydrogen can play an important role, bringing another technological possibility for the decarbonization of GHG emissions due to energy consumption in vehicles (in addition to those currently available, such as the use of biofuels, demand management for mobility, etc.), either directly through fuel cells or indirectly through synthetic fuels – e-fuels.

Accelerating the development of the low carbon hydrogen market will bring a series of business opportunities (for oil and gas, renewables, biofuels, nuclear and other industries), as there are different technological routes and inputs for their production (Hydrogen Council, 2020). The various recent initiatives linked to the development of the global hydrogen market are a reflection of these opportunities, with Brazil being a potential supplier for the domestic and international market, considering production through different technological routes. Given the magnitude of this potential market in the coming years, as well as, its impact on different sectors, the insertion of hydrogen in the Brazilian energy planning becomes fundamental.

Thus, this chapter presents a contextualization of the production chain and uses of hydrogen, focusing on emissions in different technological routes. Then, an approach is made to the current domestic market, with an estimate of technical production potential from different energy sources.

12.1 Introduction

Hydrogen has the potential to initiate a paradigm shift in the energy sector, bringing substantial opportunities to Latin America. The region can become a world leader mainly in low carbon hydrogen, considering the abundant and competitive renewable energy resources, as well as contributing to strongly decarbonize the region's industries and transportion sector.

The fact that Brazil is very competitive in renewable energies and has ample potential to be exploited translates into a strong point for the low-carbon hydrogen industry. The country also has natural gas and other important energy resources, water resources, domestic uranium resources and nuclear technology, a robust infrastructure including logistics and ports, relative distance to major potential consumer markets (Europe, for example) an solid and modern energy sector in continuous evolution, as well as human capital to develop its significant potential as a local consumer market and to take advantage of opportunities for future foreign trade in hydrogen and/or its products.

The country has been developing a hydrogen R&DI strategy for almost 20 years, focusing on the development of several technological routes: renewables (ethanol, hydro, wind and solar) and natural gas. It has developed pilot projects for buses, electric generation and energy storage, ethanol fuel cell, which aroused the interest of large companies[1], in addition to having start-ups operating commercially in hydrogen, including green hydrogen[2]. Relevant international industrial gases companies[3] have also been operating in the domestic hydrogen market and several domestic and

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[1] Like Nissan, Toyota, Volkswagen and Bosch.

[2] Like Hytron (acquired by NEA Group of Germany in November 2020), Electrocell, Ergostech, Unitech and Novocell.

[3] Like Air Liquide, Air Products, White Martins/Linde and Messer.

international companies in the energy, mineral and metallurgical sector have also announced interest in developing activities related to the low carbon hydrogen value chain in Brazil.

In 2002, the Ministry of Science and Technology (MCT) launched the Brazilian Program for Hydrogen and Fuel Cell Systems - PROCaC. Later, in 2005, this program was renamed Program of Science, Technology and Innovation for the Hydrogen Economy, with the acronym PROH2. Also in 2005, the Ministry of Mines and Energy coordinated the so-called “Roadmap for Structuring the Hydrogen Economy in Brazil”, a broad study together with the Ministry of Science and Technology - MCT, dozens of specialists from Brazil and abroad, domestic and foreign companies, institutes and research centers, regulatory agencies and metrology institutes.

During this period, it is worth noting that Brazil was the first country in Latin America to develop a fleet of hydrogen fuel cell buses. The project, carried out between 2005 and 2015, allowed the design, construction and operation of a prototype and three other buses, which circulated in a metropolitan corridor of the city of São Paulo. This had the participation of MME, EMTU/SP, UNDP and ABC/MRE, and had resources from GEF and FINEP, in addition to EMTU/SP and PNUD.

In 2010, the Center for Management and Strategic Studies (CGEE), commissioned by the MCTI, released a document, “Energy hydrogen in Brazil: Subsidies for competitiveness policies: 2010-2025”, which presented a detailed and comprehensive diagnosis about the bottlenecks to be faced, consisting of a very important starting point for the consolidation of an institutional, legal and regulatory framework that needs to be established for the flourishing of a hydrogen economy. In 2018, the MCTI's Science, Technology and Innovation Plan for Renewable Energies and Biofuels 2018-2022 established among its actions: i) to develop energy storage technologies, such as batteries (lithium, sodium, liquid, etc.), fuel, flywheels, among others; ii) to encourage demonstration projects in energy storage, focusing on batteries, fuel cells, flywheels, among other technologies; iii) to encourage demonstration projects for the use of renewable energies and fuels for the production of hydrogen for vehicular use and for the production of synthesis gas.

Existing projects for the production of renewable hydrogen (ethanol, hydro, wind and solar) in Brazil, in general, are related to government programs through public or publicly oriented R&DI funds in Brazil, such as R&D ANEEL, R&D ANP, FNDCT , FINEP, FAPESP, CNPq and FAPERJ. The total invested between 1999 and 2018 is close to BRL 200 million. The relevance of hydrogen research centers established in Brazil, such as the Renewable Energies Competence Center of the Itaipu Technological Park – PTI, the Fuel and Hydrogen Cell Research Center of the Energy and Nuclear Research Institute – IPEN (associated with USP), the Hydrogen Laboratory (LABH2) of COPPE/UFRJ, the National Center of Reference in Hydrogen Energy (CENEH) and the Hydrogen Laboratory (LH2) of UNICAMP, the laboratories of the Technological Park of the UFC, the Center of Production and Research in Green Hydrogen (CPPHV), among others.

This long-term commitment to hydrogen R&DI includes granting funds for collaborative industry-academy projects and for spin-offs and start-ups; providing tax incentives for laboratories, equipment and research to support capacity building; granting scholarships to students and researchers; and the promotion of innovation networks.

The goals were to develop technologies to produce hydrogen from natural gas, ethanol and water electrolysis through hydroelectric, wind and solar energy, as well as to develop technologies for the production of fuel cells. Other objectives were training and developing spin-offs, start-ups and companies to establish a market and a value chain. And it can be said that the initial goals were achieved.

Currently, it is observed that there are some government decisions to increase R&DI funds and give priority to hydrogen in Brazil, particularly for demonstration and commercial projects. However, it should be noted that one of the bases for the modernization of the energy sector in Brazil is the removal of subsidies and barriers to competition. In addition, there are already financial incentives and tax exemptions along low-carbon hydrogen chains, which can be reinforced, including with green finance instruments, but Brazil's fiscal conditions make granting subsidies (economic subsidies) unlikely.

In 2021, the CNPE established the Resolution No. 2, 02/10/2021, which guided ANEEL and ANP to prioritize the allocation of R&DI resources to some topics, including hydrogen, in order to expand innovations in this energy vector.

On April 20, 2021, the CNPE proposed the development of guidelines for the National Hydrogen Program (PNH2). It is a priority for Brazil to consolidate the legal framework and regulations and improve the design of the hydrogen market to ensure an adequate business environment for the promotion of private investments, including international investments in Brazil.

In parallel, throughout 2021, MME and EPE have participated in several initiatives, within the scope of Brazil-Germany technical cooperation aimed at developing the green hydrogen market, with emphasis on the “H2 Brasil” program (German / Brazilian Power- to-X Partnership Program) and for the Green Hydrogen Production, Logistics and Application Task Forces. The first program aims to improve the legal, institutional and technological conditions for the development of a green hydrogen economy in Brazil and, for that, 34 million Euros were destined to be invested in the creation of structural conditions, dissemination of knowledge, training, innovation and market expansion. The second initiative brings together companies and institutions with experience and projects related to green hydrogen and aims to share information and perceptions, as well as promote structuring/leveraging projects (forums, matchmakings, studies, etc.) and recommendations for political dialogue between Brazil and Germany.

Such initiatives are in line with the National Hydrogen Program (PNH2), whose guidelines have international cooperation as one of the thematic pillars, It is noteworthy that, although this partnership focuses exclusively on the so-called green hydrogen, as it is the element of common interest to the parties, the other national initiatives have technological neutrality in principle and also evaluate other technological routes that are promising for Brazil and that offer opportunities for decarbonization. Other international cooperation efforts in the country have also identified low-carbon hydrogen as a priority topic, such as the Brazil-US Energy Forum – USBEF, among others.

In this context, it is also worth mentioning that in order to contribute to the national strategy for low carbon hydrogen, as well as to enhance the optimization of the national energy strategy in an integrated way, EPE developed a series of studies aimed at better understanding the prospects for the production of hydrogen from natural gas in Brazil. In this sense, a Technical Note on Gray Hydrogen was prepared, which addresses the technological route of hydrogen production from the steam reform of natural gas already existing in Brazil, which is the most widespread technology worldwide.

In addition to the aforementioned technical cooperation, a partnership was signed between EPE and the British Government through the Energy Program for Brazil (BEP)[4]. Within the scope of this partnership, two Technical Notes on Blue and Turquoise Hydrogen were developed. These Notes involve the technological routes of hydrogen production from natural gas, with capture, storage and use of carbon (blue hydrogen), and from methane pyrolysis without CO2 emission, with the formation of coke (turquoise hydrogen), respectively, advancing in the understanding of the

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[4] Brazil Energy Program (BEP) provides UK funding and international expertise to support Brazil's emergence as a renewable energy powerhouse.

costs and potential of this route for the production of low carbon hydrogen in Brazil.

Such initiatives are in line with the National Hydrogen Program (PNH2), whose guidelines have international cooperation as one of the thematic pillars. It is noteworthy that, although this partnership focuses exclusively on the so-called green hydrogen, as it is the element of common interest to the parties, the other national initiatives have technological neutrality in principle and also evaluate other technological routes that are promising for Brazil and that offer opportunities for decarbonization. Other international cooperation efforts in the country have also identified low-carbon hydrogen as a priority topic, such as the Brazil-US Energy Forum – USBEF, among others.

There is, therefore, a set of governmental actions to develop the hydrogen economy in Brazil, where all production and input routes deserve attention, especially those neutral or low carbon technological ways, in order to contribute to a greater decarbonization of the economy in the future.

Box 12 - 1: Hydrogen production from natural gas and a possible strategy for Brazil

The production of hydrogen from natural gas steam reform is the most used technology, being called gray hydrogen, when its production does not involve capture and storage of CO2 (CCS) or capture, storage and use of the CO2 produced (CCUS- Carbon Capture, Utilization and Storage). This technology has high efficiency and technological maturity, and the most influential parameter is the price of natural gas. It is also noteworthy that the CO2 emissions from the process (as raw material and as fuel for the system) are relevant, so that it is unlikely that obtaining hydrogen by this route still has a relevant space in the long term, in a low carbon future.

In the Gray Hydrogen Technical Note published by EPE, a case study was developed to estimate the technical-economic feasibility for the implementation of production units in Brazil through the natural gas steam reforming route without CCS or CCUS. Hydrogen costs were estimated based on variations in two factors: plant capacities and natural gas prices. Plant capacities were considered between 20 and 1000 t H2/day and gas prices ranged between 4 and 12 USD/MMBtu. Thus, estimates of hydrogen production costs were between 9 and 25 USD/MMBtu (from USD 1.02 to 3.36/kg H_2). If the cost of 6 USD/MMBtu for natural gas is considered, the cost of producing H2 would be between 12 and 16 USD/MMBtu (from USD 1.37 to 2.15/kg H_2).

In blue hydrogen, the autothermal reforming (ATR) technology stands out and its greater compatibility with obtaining low-carbon hydrogen. It is noteworthy that this technology, although not yet widespread, already has projects in activity worldwide. Regarding carbon utilization projects, the synergy between the hydrogen production enterprise and the one that receives CO_2 stands out. Regarding storage, different types of geological reservoirs have been studied, presenting different physical and chemical entrapment mechanisms that allow the effective sequestration of CO_2. In studies with the participation of EPE, for the Brazilian scenario, the possibility of using offshore platforms for the installation of hydrogen production plants was raised, in order to facilitate access to pre-salt natural gas and store CO2 in rocks in that environment.

In the Blue Hydrogen Technical Note, two case studies were considered, including the hydrogen production costs of the Gray Hydrogen Technical Note and incorporating the estimates of CO_2 capture, transport and storage costs. In the onshore case, hydrogen production would be in Cubatão/SP and CO_2 injection would be in the Merluza field (offshore), resulting in costs ranging between 23 and 274 USD/MMBtu. In the offshore case, hydrogen production would be in the Santos Basin and CO_2 would be injected in the same area, obtaining costs between 33 and 250 USD/MMBtu. In both case studies, the same ranges of plant capacities and natural gas prices described in the Gray Hydrogen Technical Note were used. Additionally, if the commercialization of carbon credits (25, 50 and 100 USD/t CO_2) is considered, hydrogen production costs would be reduced by approximately 2, 4 and 8 USD/MMBtu, respectively.

With regard to turquoise hydrogen, which is produced by pyrolysis of methane with the production of solid carbon and, consequently, without CO_2 emission in the process, it can be noted that its production involves a technology that is still evolving, which therefore demands development. However, theoretical studies already show that this route can become economically and environmentally viable and that it depends on the added value of carbon and the market's ability to absorb this product.

Box 12 - 1: Hydrogen production from natural gas and a possible strategy for Brazil

Production costs and demand for carbon and hydrogen will be key factors in determining optimal production capacity and location of turquoise hydrogen production plants. To assess the potential of this route, a case study was carried out that proposed the construction of a plant located in a region close to the Brazilian coast and petrochemical complexes. The cost of producing turquoise hydrogen was calculated using as assumptions the price of natural gas equal to 6 USD/MMBtu and the selling price of black carbon equal to 0.20 USD/kg, obtaining the cost of hydrogen production equal to 19.3 USD/MMBtu (from USD 2.20 to 2.60/kg, depending on the calorific value used), verifying that the production and sale of carbon black reduces the net cost of hydrogen by this route.

Although the use of CCS or CCUS technologies as in blue hydrogen or even the production of hydrogen without CO2 production, as seen in turquoise hydrogen, can raise the production costs of hydrogen, compared to that produced through the gray route, the possibility of negotiation of carbon credits, as well as the sale of products with higher added value (solid carbon) could increase the attractiveness of these processes in the coming years.

The blue and turquoise hydrogen production routes have the potential to generate flexible and clean energy from an abundant fossil fuel, natural gas. These routes open up opportunities for the gas chain to play an essential role in energy and the low carbon industry, expanding the role of transition fuel generally assigned to natural gas. Thus, the role of the blue (with CCS or CCUS) and turquoise (without CO2 production) routes in the coming years is highlighted, due to the lower levels of CO2 emission from these processes.

12.2 Dynamics and Uses of Hydrogen

12.2.1 DYNAMICS OF THE HYDROGEN CHAIN

The hydrogen chain is already established, with a large number of producing and consuming players, and research and development institutions, as pointed out in the document “Bases for the Consolidation of the Brazilian Hydrogen Strategy”, published by EPE in February 2021, and revised in June of the same year.

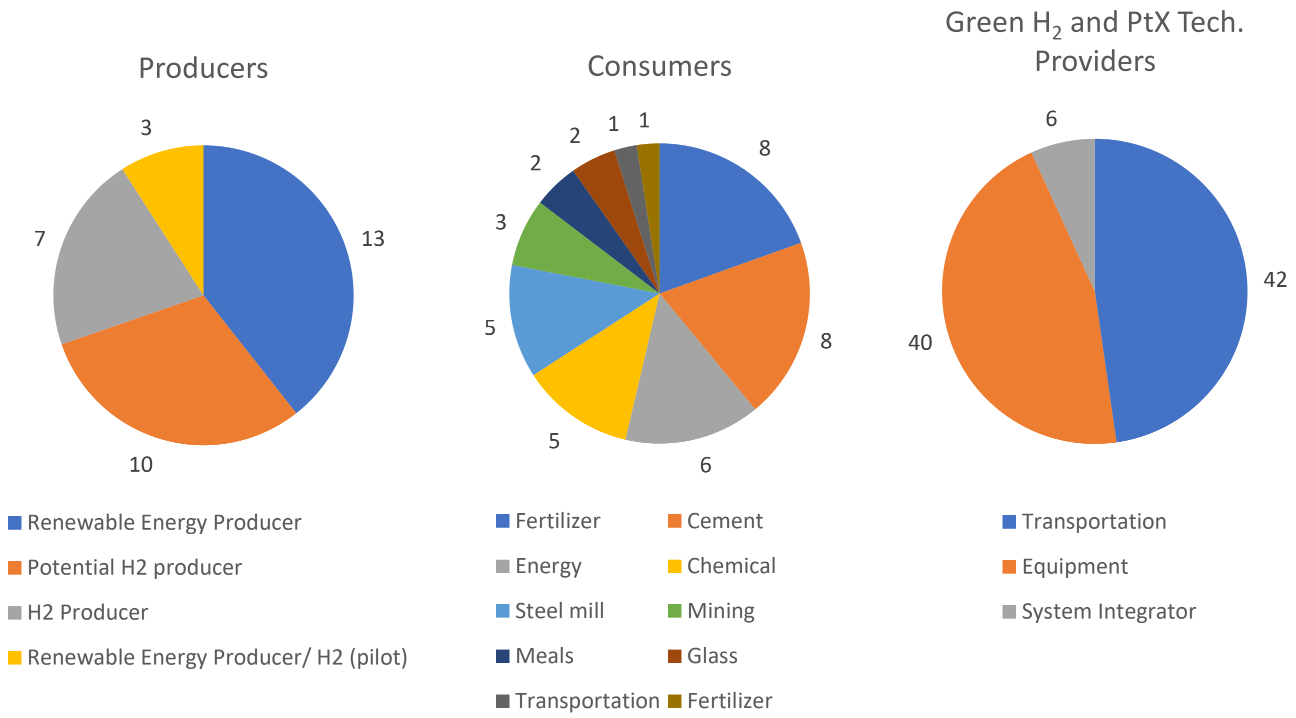
The GIZ study (2021) mapped the main active or with potential for future operations actors in the hydrogen production chain in Brazil, having identified 203 actors among producers, consumers, technology suppliers, service providers, sectoral representations, universities and R&D centers. A summary of the results is shown in **Table 12 - 1** and **Figure 12 - 1**.

Table 12 - 1: Main active or with potential for future operations players mapped in Brazil

types of players	Number of players
Consumers	41
Green H_2 and PtX technology providers	88
Service providers	13
Producers	33
Sectoral representations	12
Universities R&D Centers	16
Grand Total	**203**

Source: Prepared from GIZ (2021).

Figure 12 - 1: Detailing the types of players in the Producers, Consumers and Technology Suppliers categories

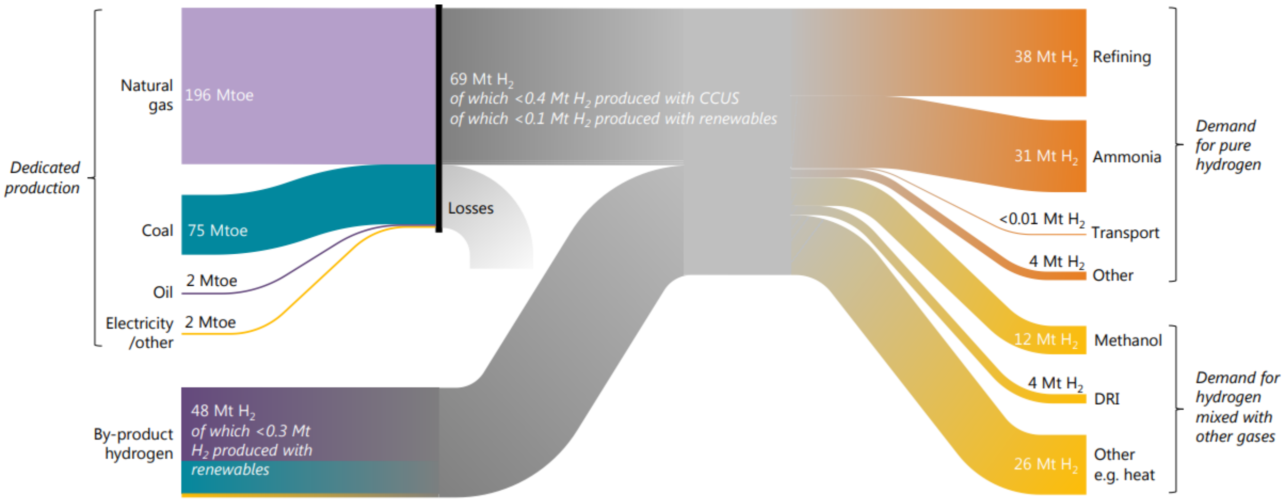


Source: Prepared from GIZ (2021a).

However, the supply of hydrogen in this existing market is almost exclusively based on fossil sources; and the demand is almost entirely for industrial purposes (use as raw material). The issue of climate change, with the consequent need for a low carbon energy grid, has guided the efforts of the world's main economies towards the development of renewable and clean sources of energy, and the energy use of hydrogen. The International Energy Agency (IEA) itself points to hydrogen and its products as one of the pillars of decarbonization, in its report “Net Zero by 2050”, published in May 2021.

Almost all of the world's hydrogen supply, estimated by the IEA for 2018 as 115 Mt, is based on steam reforming of natural gas and coal. In addition, the applications that most consume this hydrogen (pure or as a component of synthesis gas) are petroleum refining, ammonia production and methanol production, adding up to 70% of the total. Another prominent use is in the direct reduction of iron ore. The remainder of the consumption of this hydrogen, an amount that reaches 30 Mt, is distributed in several other applications. The Sankey diagram presented in Figura 12 – 2 shows the hydrogen chain today, from production (dedicated and as a co-product) and sources used, to applications. In general, these uses of hydrogen are not for energy purposes, but as an input or utility in industrial processes.

Figure 12 - 2: Current representation of the hydrogen chain



Source: IEA (2019).

The amount of hydrogen consumed worldwide in uses currently known as “Others” is significant, 26% of total consumption, so it is also interesting to know them. **Table 12 - 2** presents some uses that fall into this category.

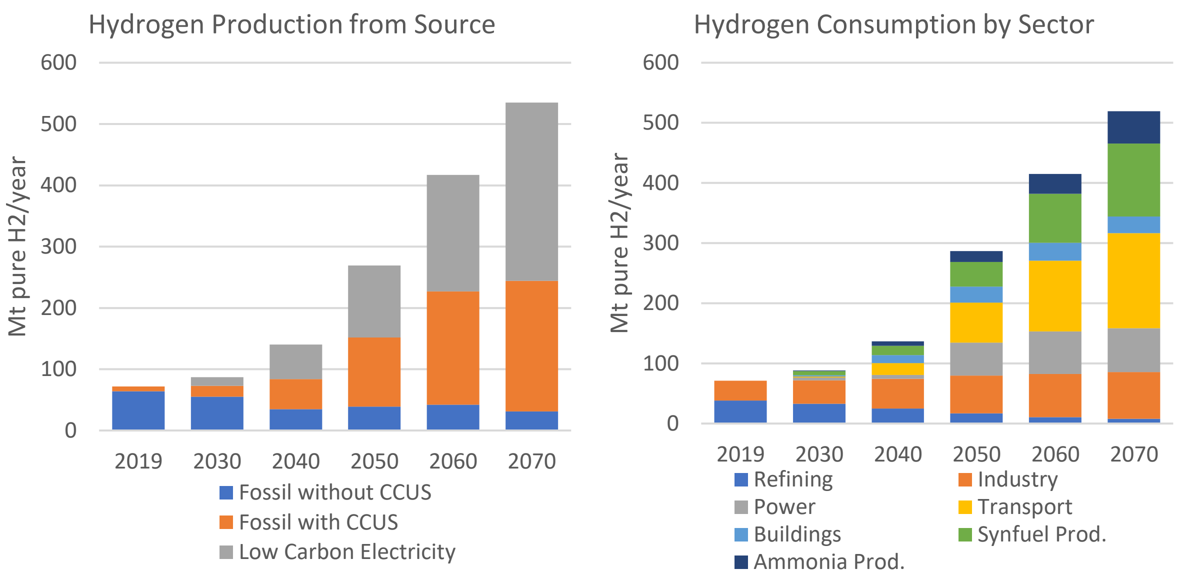
Table 12 - 2: Main players or with potential for future operations mapped in Brazil

Sector type	Hydrogen use description
Foodstuffs	Used to turn unsaturated fats into saturated fats and oils, including hydrogenated vegetable oils such as margarine.
Steelmaking	Used in various applications, including metal alloys and flash calcining of iron ore
Welding	Atomic hydrogen welding, arc welding process that uses a hydrogen atmosphere
Flat Glass	A mixture of hydrogen and nitrogen is used to prevent oxidation and therefore defects during manufacture
Electronics	As an efficient reduction and etching agent, hydrogen is used to create semiconductors, LEDs, displays, photovoltaic components and other electronics
Medical	Hydrogen is used to produce hydrogen peroxide (H_2O_2). Recently, hydrogen has also been studied as a therapeutic gas for a number of diseases.

Source: https://wha-international.com/hydrogen-in-industry/ (queried on 07/05/2021).

In prospective terms, the IEA's sustainable development scenario up to 2070 points out that the origin profile of hydrogen shows a gradual change, being produced predominantly from electricity obtained from renewable energies and fossil fuels associated with CCUS. From the point of view of the consumption profile, in this scenario, it is estimated that the energy use of hydrogen and its products should be predominant, with emphasis on the use in the transportion sector. On the other hand, the destination of hydrogen for the refining sector points to a continuous drop in this timeframe (**Figure 12 - 3**).

Figure 12 - 3: World production of pure hydrogen by source and world consumption of pure hydrogen by sector, in the IEA sustainable development scenario, 2019 to



Source: IEA (2021).

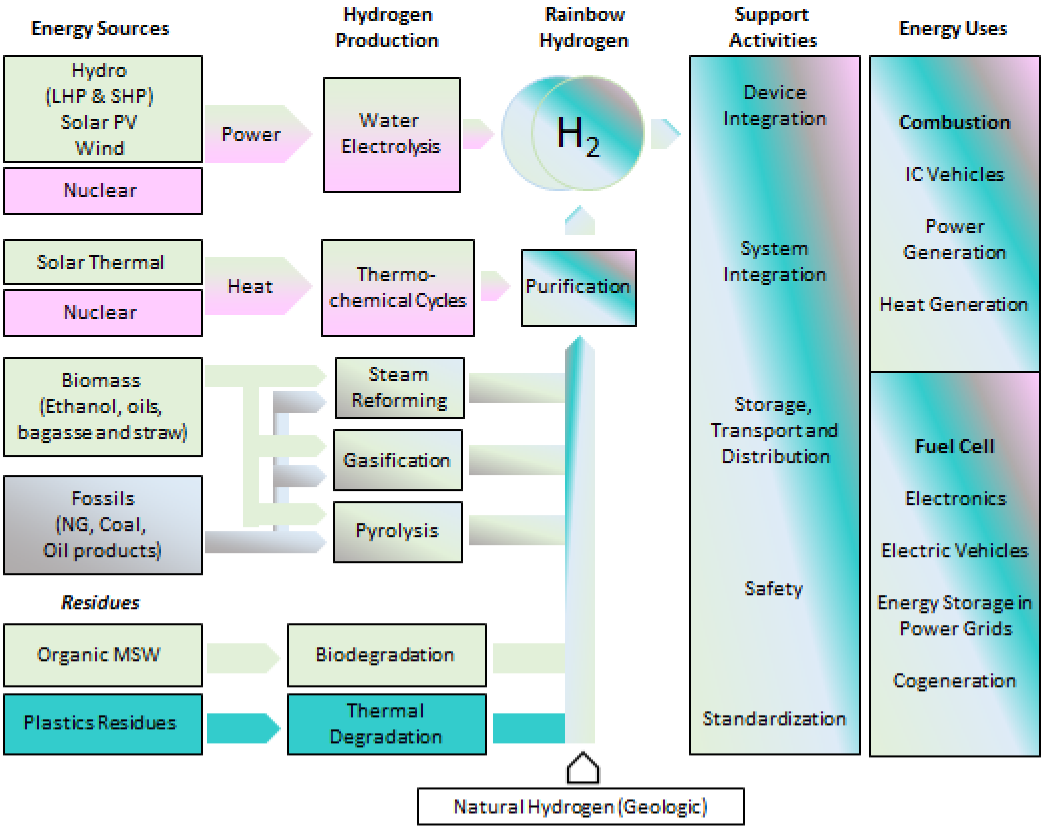
Toward introducing hydrogen into the energy mix, and expanding its uses, the offer of low carbon hydrogen to replace fossil energy sources involves both the use of non-fossil energy sources and fossil energy sources with CCUS. **Figure 12 - 4** presents a simplified representation of the technological routes for the production of hydrogen, with a synthesis of the classification of hydrogen in a color scale shown in **Table 12 - 3**.

Even so, to facilitate the reference to the other routes and to use the usual market jargon (brown, gray, blue and green), it is proposed for hydrogen produced from biomass or biofuels with or without CCUS, through catalytic reforms, gasification or anaerobic digestion with moss green color (with variations in shades of green that can range from “brown”, in the case of significant changes in land use, to “greenish”, in the case of zero or negative carbon). However, it is suggested that the classification of the different forms of hydrogen should proceed from a more objective assessment, moving away from the color-based approach, commonly used.

In addition to considering the life cycle of greenhouse gas emissions used in hydrogen production and transport processes, other sustainability criteria must also be taken into account, such as conservation of natural resources, pollution management and control, conservation biodiversity and ecosystems, etc.

Table 12 - 4 presents values of carbon intensity for some technological routes of hydrogen production

Figure 12 - 4: Representation of hydrogen technological routes



Source: Adapted from CGEE (2010)

Table 12 - 3: Classification of hydrogen in color scale

Color	Classification	Description
⬛	Black Hydrogen	Produced by coal (anthracite) gasification without CCUS
🟫	Brown Hydrogen	Produced by coal (lignite) gasification without CCUS
◼	Gray Hydrogen	Produced fom Methane Steam Reforming without CCUS
🟦	Blue Hydrogen	Produced fom Methane Steam Reforming with CCUS
🟩	Green Hydrogen	Produced from water electrolysis with renewable power
⬜	White Hydrogen	Produced from geological reactions (natural occurence)
🟦	Tourquoise Hydrogen	Produced from Methane Pyrolisis (Carbon results as a solid byproduct)
🟩	Moss Hydrogen	Produced from biomass or biofuels via cathalitic reforming or anaerobic digestion, and from gasification of plastic waste
🟪	Pink Hydrogen	Produced from electrolysis with nuclear power generation

Table 12 - 4: Carbon dioxide emissions in the life cycle of hydrogen production by technological route in the world

Technology	Carbon Intensity ($kgCO_2/kgH_2$)
Steam Methane Reforming	10.1 - 17.2
Coal gasification	14.7 - 26.1
Methane pyrolysis	4.2 - 9.1
Biomass	0.3 - 8.6
Electrolysis (Natural Gas Combined Cycle)	23.0
Electrolysis (Wind)	0.5 - 1.1
Electrolysis (Solar)	1.3 - 2.5
Electrolysis (Nuclear)	0.5 - 1

Source: TENHUMBERG & BÜKER, 2020.

The greenhouse gas (GHG) emissions in the hydrogen life cycle, included in this data (**Table 12 - 4**), include emissions from the extraction of inputs, utilities and materials to the hydrogen production process. To consider the use of hydrogen, it is necessary to know the life cycle emissions of the materials needed to build the infrastructure for this use. In the case of plasma pyrolysis of methane, the resulting carbon is obtained in solid form, reducing and even canceling emissions.

Centralized, Distributed and Onboard Hydrogen Production

The capacity of a hydrogen production plant can vary according to need or opportunity. Centralized production, in plants with high production capacity, allows for economies of scale, but requires an important storage and distribution infrastructure. In the case of distributed production, this infrastructure is less relevant in terms of costs, but the project can lose out on economies of scale. The distributed production of hydrogen, however, makes it possible to scale the plant to serve local markets.

The boundary between these two classifications is not rigid. The National Renewable Energy Laboratory (NREL), in a study analyzing the leveled cost of centralized and distributed hydrogen production, considers as centralized production plants with a capacity of 50 to 820 t of hydrogen per day, and as distributed production plants with a capacity of up to 1.5 t of hydrogen per day (NREL, 2009).

Centralized and distributed production are stationary. On even smaller scales, there is the on-board production of hydrogen, which allows mobility. Thus, vehicles can be fuelled with other energy sources, such as ethanol (Nissan, 2021), methanol (Karma & Blue World, 2021), dimethyl ether (Bianchini et al., 2021), etc. and carry out the reform to produce hydrogen that powers the fuel cell. At this scale, hydrogen can also be used in electric power distribution networks to facilitate system operation (GHD, 2020).

12.2.2 CURRENT MARKET

According to the International Energy Agency, in 2018, the world demand for hydrogen totalled 115 Mt, of witch 73 Mt was pure hydrogen (IEA, 2019). Ammonia production for fertilizer and petroleum refining accounted for 96% of the demand for pure hydrogen. The demand for hydrogen in mixtures with other gases ammounted 42 Mt, with methanol production accounting for

29%, direct reduction in the steel industry accounted for 7%, and the remainder in other diverse uses (IEA, 2019).

The main technological route in the world is the steam methane reforming from natural gas (gray hydrogen), in hydrogen generation units (UGH), about 70% (IEA, 2019). Water electrolysis with renewable energy (green hydrogen) accounts for only 1% (IEA, 2019). The remainder is based on the gasification of coal (mostly) and oil products, as co-products in the catalytic reforming process (mainly) and in other units (catalytic cracking - FCC and hydroprocessing - HCC, to a lesser extent) in refineries (IEA, 2019; Szklo and Uller, 2008).

The Brazilian market is mainly to meet the demands of refineries and fertilizer plants (87%), and hydrogen is produced and used locally. In Brazil, the demand for hydrogen reached around 1 Mt in 2010, 50% for fertilizers, 37% for refining, 8% for chemicals and 4% for metallurgy/food, with 95% of fossil origin - predominantly natural gas (César et al., 2019).

With regard to consumption by fertilizer factories, the demand for hydrogen has been reduced to lower levels in Brazil, around half in recent years, mainly due to: methanol plant of GPC Química in Rio de Janeiro/ RJ shut down in September 2013; indefinitely shut down of Copenor's Methanol Plant in Camaçari/BA since July 2016; temporary shut down of Petrobras nitrogen fertilizer plants in Bahia (Fafen-BA) and in Sergipe (Fafen-SE) in June 2018; and temporary shut down of the fertilizer factory located in the city of Araucária/PR in January 2020. However, Fafen-BA and Fafen-SE were leased for 10 years to Proquigel Química in August 2020. Fafen-SE and Fafen-BA, now Unigel Agro SE and Unigel Agro BA, resumed operations in March and November 2021, respectively.

As for refineries, the demand for hydrogen is mainly destined for hydroprocessing and hydrotreating, aiming, respectively, at greater recovery of middle distillates (diesel and aviation kerosene, for example) and quality adjustments of the fuels produced, since specifications delimit the maximum sulfur content for the commercialization of fuels, such as gasoline and diesel oil. Hydrotreatment is the most used industrial process for the removal of sulfur, nitrogen and aromatic compounds from streams in a refinery, with hydrogen being used as a capture element.

In Brazil, in 2020, around 325 thousand tonnes of pure hydrogen were produced in refineries. Although oil refining is an important producer of hydrogen in the country, it is noteworthy that, in the current scenario, this volume is used for internal consumption in hydrotreatment processes. Petrobras, the main player in the Brazilian oil refining sector, plans to produce 100% of diesel with very low sulfur content (10 p.p.m) by 2026, indicating an increase in its hydrogen consumption in the coming years (Petrobras, 2021). In 2031, a consumption of around 375 thousand tonnes is forecast.

Therefore, most of the hydrogen produced is priced based on internal price transfers or bilateral contracts. According to **Figure 12 - 5**, it is estimated that the costs of gray hydrogen (from Steam Methane Reforming - SMR) ranges from US$ 0.9 to US$ 3.2 per kg H_2. In turn, blue hydrogen (SMR with CCUS) it is estimated that these costs can range from US$ 1.5 to US$ 2.9 per kg H_2 in Brazil. It should be noted that the ranges of values presented show a comparative view of the hydrogen production routes, although observations outside these ranges can be verified, in specific projects, depending on local conditions and/or applicable business models.

With regard to biomass, moss green hydrogen can be obtained from gasification, pyrolysis or through the use of ethanol in a fuel cell, as already illustrated in **Figure 12 - 5**. For ethanol, experts say the cost could range from US$ 2.5 to US$ 10.59 per kg H_2, as of today (in Brazil, it would be US$ 2.5-5 per kg H_2). For green hydrogen it would range from US$ 3 to US$ 7.5 per kg H_2, as shown in Figure 12-5. In a study carried out for EPE and the MME (Report on Green Hydrogen in Brazil), through GIZ, by Tractebel Engineering GmbH, within the scope of the German Brazilian Technology Partnership for Energy Storage - DKTI, it ratifies this magnitude of costs in Brazil, with values in the range of US$ 2.19

to US$5.19 per kg H2, considering cases with different characteristics and/or locations (GIZ, 2021b).

Table 12 - 5: Overview of hydrogen production results by simulated case

Scenario	A1	A2	P1	E1	E2	E3
Electricity production installed power (MW)	295	207	339	400	2,392	-
Electricity production (MWh/year)	975,882	319,879	1,120,751	1,321,205	7,909,664	-
Electricity surpluses for sale (MWh/year)	182,311	18,021	278,215	639,288	4,498,862	-
Electricity consumption for producing H_2 (MWh/year)	746,996	283,151	793,087	682,917	3,410,802	3,410,802
Electricity consumption for producing NH_3 (MWh/year)	46,575	17,654	49,449			
Hydrogen production (t/year)	14,389	5,454	15,277	13,140	65,700	65,700
Compliance to the additionality criterion (S/N)	Yes	Yes	Yes	Yes	Yes	No
Electrolyser size (MW)	100	100	100	95	465	385
Total H_2 plant power (MW)	105.6	105.6	105.6	100.5	491.3	406.0
Electricity Cost[1] (USD/kWh)	0.033	0.069	0.031	0.039	0.039	0.030
LCoH (USD/kg H_2)	3.67	5.19	3.73	4.66	4.94	2.19
LCoA[2] (USD/t NH_3)	1,027	1,447	1,010	-	-	-

Notes: (1) Corresponds to the cost of electricity used to produce hydrogen. It does not necessarily correspond to the levelized cost of the power generation plant, due to the sale of surplus generated to the grid.
(2) For the estimation of the levelized cost of production of ammonia (LCoA) in existing units, data that are not public are required. Thus, in some cases presented in the table, only the levelized cost of hydrogen production (LCoH) is estimated.

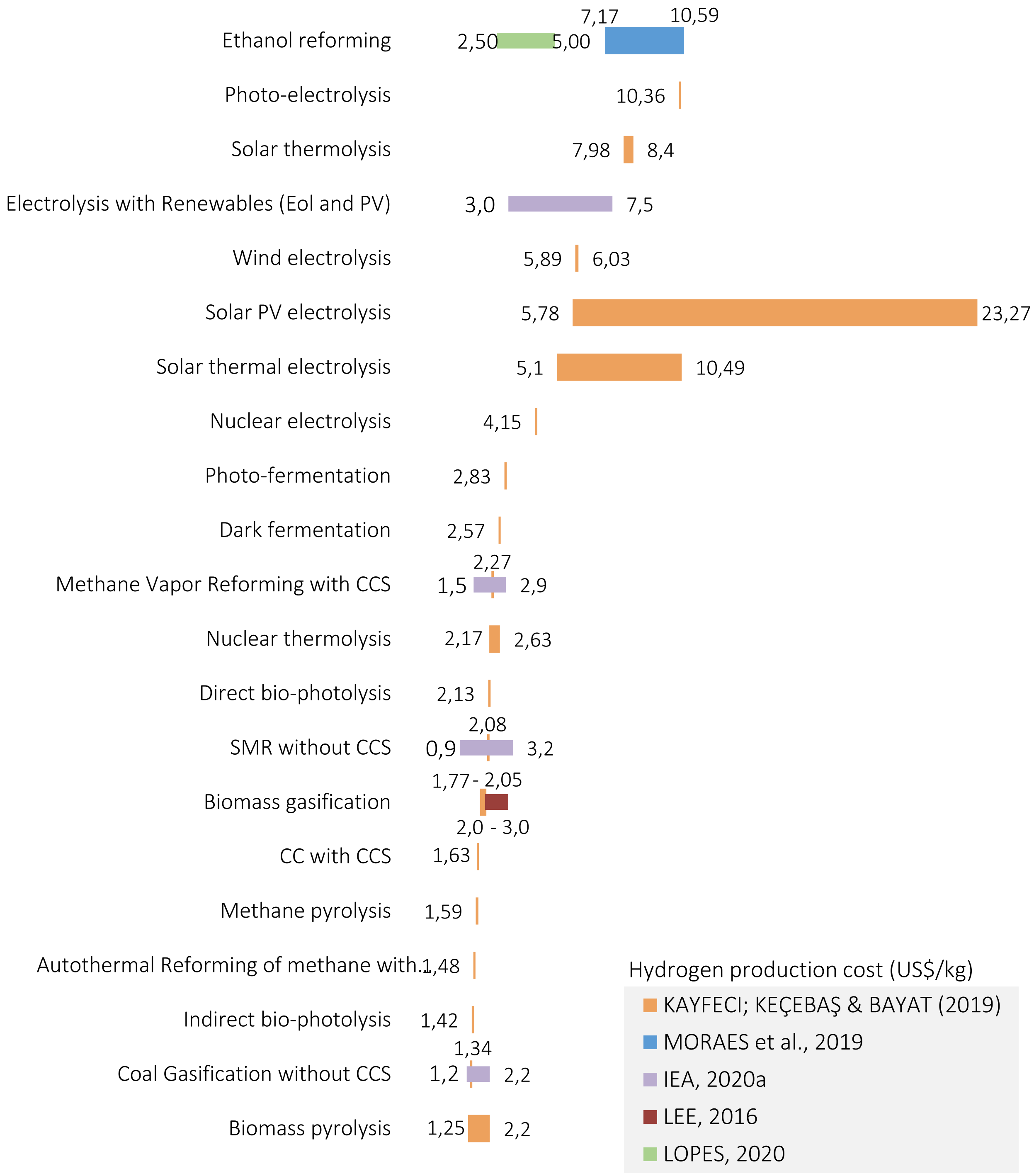
Glossary of simulated cases:

1. Case A1: ammonia production near the Port of Aratu (BA) - Electricity acquired from a wind power plant located in the state of Bahia
2. Case A2: ammonia production near the Port of Aratu (BA) - Electricity acquired from a solar photovoltaic plant located close to the hydrogen production plan
3. Case P1: ammonia production near the Port of Pecém (CE) - Electricity acquired from a wind power plant located in the state of Ceará
4. Case E1: Production of ammonia in an existing plant, from a partial supply of green hydrogen (20% of the total powe rsupply)
5. Case E2: Production of ammonia in an existing plant, with 100% supply of green hydrogen
6. Case E3: Ammonia production in existing plant, with 100% green electricity purchased on the free market

In addition to the small scale moss green hydrogen and water electrolysis plants at the Itaipu Binational hydroelectric plant (PTI), it is worth mentioning the commissioning of an electrolyser for R&D in energy generation and storage in the area of the Itumbiara de Furnas Power Plant in March 2021. At first, this project would run on power from a hydro, but it is now being adapted to run on solar PV too.

It is also important to note that the cost of gray hydrogen, around US$ 1 / kg in the most competitive countries, is much lower than those of blue hydrogen (from US$ 1.5 to US$ 2.9 / kg) and green hydrogen (from US$ 3 to US$ 7.5 / kg) are, as shown in the following figure. It should be noted that, in 2021, the price level for hydrogen from natural gas routes might have changed with the rise in natural gas prices, although this depends on the pricing arrangements (contractual relationships or transfer prices).

Figure 12 - 5: Hydrogen production cost



There are also high expectations about the competitiveness of natural or geological hydrogen (estimated to be cheaper than fossil fuel and electrolysis routes), especially when available as a mixture with helium gas (Prinzhofer et al., 2018).

The Australian Department of Energy and Mining presented, in 2021, a proposal for the licensing of exploration activities of natural hydrogen[5]. Research indicates that Brazil may have relevant natural or geological hydrogen potential in at least four states (Project by the companies GEO4U and Engie Brasil): Ceará, Roraima, Tocantins and Minas Gerais (Moretti et al., 2021; Prinzhofer et al., 2019).

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[5] See https://www.petroleum.sa.gov.au/geology-and-prospectivity/hydrogen#licensing

12.2.3 TECHNOLOGICAL OUTLOOK

While the energy sector sees the emergence of several technological alternatives to decarbonize around the world (hydro, wind, solar, biomass and nuclear, for example), some industries (mainly those whose industrial processes require fossil fuels) and the transportion sector present challenges in finding a way to reduce their carbon emissions (IEA, 2020c). Energy efficiency is always an option, but policies and actions are usually restricted to replacing machines and equipment, since changing industrial processes and transportion systems is not so easy.

Light-duty vehicles (Passenger cars) have some technological alternatives with biofuels (mainly, in Brazil and in the USA), hybridization, electrification (the battery, which is already more widespread, the fuel cell and synthetic fuels - e-fuels -, which still have modest entries). However, fossil fuels, such as gasoline and diesel, are still the dominant the energy source in the transportion sector. Some countries are developing legislation to ban sales of new internal combustion engine (IC) vehicles and to eliminate them from the streets and the roads. Enormous challenges for decarbonization lie ahead for heavy road transportion (mainly cargo such as long-haul trucks), aviation and maritime sector, iron and steel, chemicals, cement and mining, to ensure sustainability for decades to come (IEA, 2020c). On the other hand, business opportunities also arise in this context.

In the transportation sector, fuel options such as biofuel blends for long-haul trucks (biodiesel, Hydrotreated Vegetable Oil (HVO) or "green diesel" and biogas), for aviation (aviation biokerosene) and for maritime (biobunker) will certainly play a role for a while, as well as lower carbon fossil fuels such as natural gas (mainly LNG for trucks and ships) and synthetic fuels (synthetic aviation kerosene based mainly on GTL or CTL with CCS). These are options considered by the International Civil Aviation Organization (ICAO) in its International Aviation Offsetting and Reduction Scheme - Corsia (ICAO, 2018) and by the International Maritime Organization (IMO) in its Vessel GHG Emissions Reduction Strategy (IMO, 2018). However, such technological routes, in general, mitigate emissions, but do not drastically reduce them (except for some biofuels).

Therefore, since hydrogen is a potential energy vector for decarbonization, especially in the aforementioned sectors (including individual transport), it is also worth discussing the technological perspectives of its production and logistics. Currently, there are a few options for storing and transporting hydrogen. However, these processes are still challenging, since the density of this fuel is very low. Storage can be done in geological structures (such as mines, salt caves, etc.), but it needs suitable conditions. Another alternative is to convert them into products, such as ammonia and methanol, in order to facilitate their transport and handling to the final destination, where reconversion to hydrogen may be necessary. As storage and transport alternatives, hydrogen adsorption, liquefaction and compression can also be listed.

With regard to production, the pilot projects under development, in different routes, which will contribute to the identification and overcoming of the challenges for the gain of scale, stand out. In the case of the so-called “pink” hydrogen, for example, the flexibility conferred by the water electrolysis process can be an opportunity for nuclear power plants. There are designs of Small Nuclear Reactors – SMR (the acronym in English) that privilege this duality of function (electrical and hydrogen generation).

On the other hand, the electrolysis process requires a steady supply of electricity in order to maximize its capacity factor and the competitiveness of the hydrogen produced. For example, an electrolyser supplied, for example, by a single plant of variable renewable source, without connection to the interconnected system, would be subject to the availability and variability of electricity generation, reducing its efficiency. Therefore, its connection to the network would make more sense, which leads to the discussion about the principle of additionality, as it is happening today in Europe[6]. By this criterion, the energy consumed must be supplied by additional renewable generation, ensuring that this consumption does not lead to a possible greater generation from fossil sources. There is, however, no consensus on how to prove this requirement, both in the production and transport of hydrogen, which can discourage investments, increase project deadlines (since, in general, electrolysis plants can be built in less time than other power generation options) and jeopardize the energy transition and decarbonization (European Commission, 2021).

As discussed in chapter 3 (Centralized Generation) of this PDE, the competitiveness of domestic hydrogen will have a direct impact on the energy sector as a whole, affecting the demand for inputs. In the specific case of the electricity sector, the impact is expected both on the demand for electricity, to be used in electrolysers, for example, and on the expansion of generation, to serve these consumers, with emphasis on renewable sources, with an eventual impact in expanding the transmission network.

12.3 Technical potential for hydrogen production in Brazil

With a view to providing an order of magnitude of the Brazilian potential for hydrogen production in the coming decades, in this section, the remaining resource base to supply the domestic energy demand and the technical potential of low carbon hydrogen production in Brazil are estimated (see box below for differentiation between technical, economic and market potential). The technical potential for the production of low carbon hydrogen presented in this PDE 2031 is estimated based on the inventory of energy resources and the energy demand from the Challenge of Expansion Scenario[7] from the National Energy Plan – PNE 2050. It should be noted that low-carbon hydrogen from natural or geological resources is not included in this technical potential, since it still requires further discussion about the available estimates of potential. In other words, the technical potential of hydrogen in Brazil can still be reviewed, as research and technologies advance.

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[1] Directive 2018/2001 of the European Parliament provides, in its article 27, the details of this requirement, but only for the transport sector. Extension to other sectors is discussed.

[7] The PNE 2050 Challenge of Expansion Scenario considers relevant growth in demand and is related to a context that imposes on the planner, in addition to the need to reinforce and improve the mechanisms and policies in force, also to seek innovative solutions that allow the establishment of a strategy of long-term expansion of the energy sector in order to guarantee the supply of energy to society in the 2050 timeframe, meeting energy security, adequate return on investments, availability of access to the population and socio-environmental criteria.

Box 12 - 2: What do the different potentials tell us?

Indicating potential resource availability is a fundamental step in signaling opportunities for evaluating any market. It is important, however, to keep in mind that there are different concepts to report this potential, categorized into three types, whose relationship is shown in the following figure, in the form of subsets.

Figure 12 - 6: Schematic representation of the relationship between technical, economic and market potentials

Note: subsets are not represented to scale, which may vary depending on the situation and dynamically over time.

In this categorization, the technical potential corresponds to the upper limit of resource availability, which would be obtained if all the available resource were recovered with the most efficient technologies available, from proven and probable energy resources, admitting, therefore, a greater level of uncertainty in their availability. In this estimate, economic aspects or any other impediment to technological penetration, financial, behavioral aspects, or existing barriers to the use of this energy resource are not considered. One can consider the technical potential as the upper limit for the use of these resources. It should be noted that significant changes in technology and resource base could change the technical potential over time.

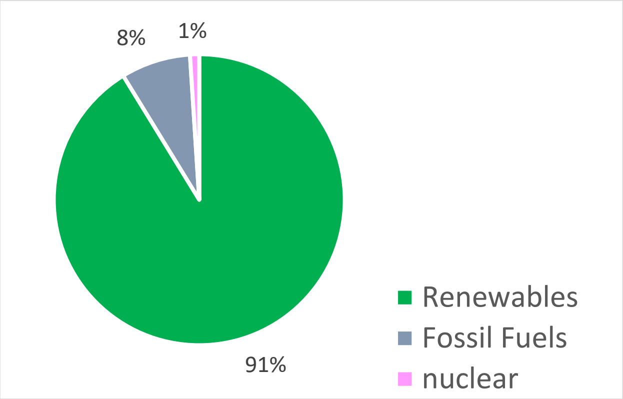
The economic potential, in turn, takes into account the penetration of technologies to take advantage of these resources that are economically viable in terms of their implementation. In estimating this potential, investments in equipment, O&M, input cost, energy sales prices, sectoral discount rates, among others, are considered. However, aspects related to existing barriers to technology adoption, access to capital, management of business priorities or perception of project risk (which would require an additional premium over the sectoral discount rate), for example, are not considered. Additionally, with regard to the availability of energy resources, those with a greater degree of certainty are adopted.

The market potential, in turn, corresponds to a subset of the economic potential, considering the viable uses from an economic-financial point of view and considering those that overcome existing barriers such as information asymmetries, difficulty in accessing capital to finance investments operations etc. In this potential, however, some barriers may be present that will prevent its full penetration, and public policies to overcome these barriers may be needed.

In the accounting of the potential of energy resources from PNE 2050 results, different approaches were adopted according to the origin of the resources. Fossil resources were computed as the accumulated expected production until 2050. For nuclear resources, it was considered the total uranium reserves. And, for the renewable resources it was considered the potential in 2050, since because of their flow nature they cannot be accumulated in the long term. The energy resources considered totalled 21.5 Gtoe of non-renewables; being 88% fossil and 12% nuclear. The fossil resource[8] with the highest volume was Oil (8.3 Gtoe), followed by Steam Coal (7.2 Gtoe) and Natural Gas (2.8 Gtoe). The nuclear resource totalled 2.4 Gtoe. Renewable resources totalled, at least, 7 Gtoe on an annual basis. The renewable resource with the greatest potential was Solar Energy with 5.3 Gtoe, followed by Wind with 1.4 Gtoe (both mostly offshore, with 98%). Other renewable resources, which include surplus sugarcane biomass, livestock biogas and energy forests, added up to 612 Mtep per year. It should be noted that this is a base estimate of remaining resources, which is the first step for prospective studies on the technical, economic and market potential for energy planning.

The potential of energy resources from PNE 2050 was adjusted to an annual basis, totaling 7.9 Gtoe/year, from 2020 to 2050 Figure 12 - 7 shows these values, by type of energy source, and more detailed data are available in Annex B.

Figure 12 - 7: Composition of the energy resources, on an annual basis, until 2050



From this amount of energy resources, the final demand of energy sources (6.8 Gtoe, see Annex B for details) of the Challenge of Expansion Scenario was subtracted. Almost 1/4 of the potential energy resources. The accumulated demand of fossil sources until 2050, of 6.6 Gtoe, leads to the depletion of 36% of the stock of fossil resources in the period.

It is worth noting that, in the case of electricity, only the final demand in 2050 was considered. For the other sources, the accumulated final demands in the period from 2020 to 2050 were considered.

Additionally, it was assumed that the electricity demand would be met entirely by renewable onshore resources (hydro, solar and wind), which are cheaper and have a higher hydrogen conversion factor. **Figure 12 - 8** shows that considering only the energetic dimension of demand this assumption is a plausible one. This approach also indicates that green hydrogen could be produced in Brazil, from these renewable sources, with no emission leakages to other sectors. Also, the surplus biomass was entirely allocated to hydrogen production. However, it is observed that, in practice, meeting the electrical demand has other requirements, in addition to energy availability, other sources, including non-renewable ones, must

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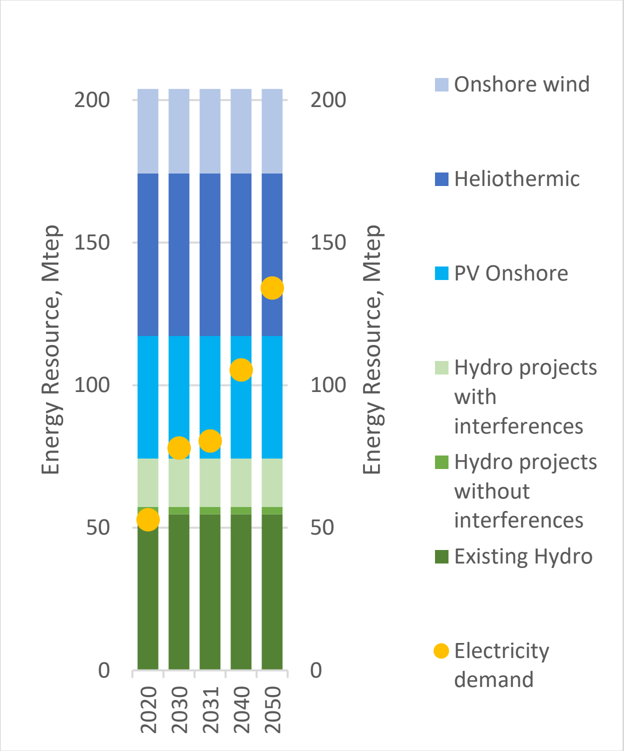
[8] These values for fossil resources have been updated to base year 2020.

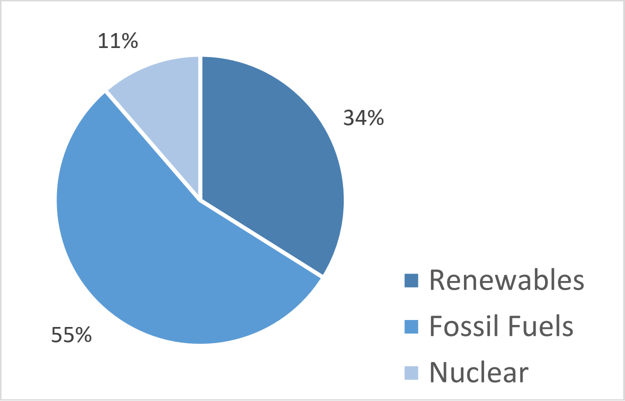
continue to participate in the Brazilian energy mix, in order to guarantee security in supply, reliability, etc. Thus, the potential of green hydrogen that would meet the additionality criterion must be even greater than that indicated in this document.

Figure 12 - 8: Meeting electrical demand and producing low-carbon hydrogen with onshore renewable resources



The amount of energy resources available for hydrogen production, obtained by subtracting the final demand from the potential of energy resources, is 21 Gtoe. Figure 12 – 9 shows the composition by type of resources. It was considered that the remaining fossil and nuclear resources were exhausted for hydrogen production in the period.

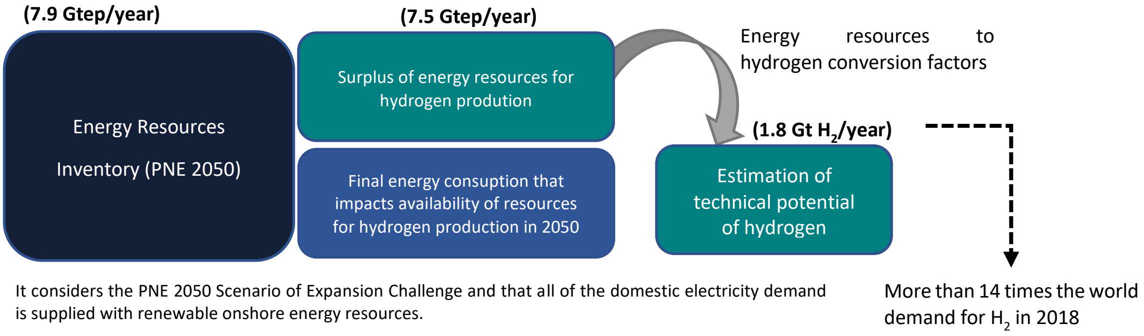
Figure 12 - 9: Composition of the energy resources available for hydrogen production



The technological routes adopted in this estimate, for the conversion of energy resources into hydrogen, are presented in Annex B, as well as the conversion factors adopted.

The methodology used to calculate and estimate the total technical potential for hydrogen production in Brazil until 2050 is presented in **Figure 12 - 10**, totaling 1.8 Gt/year, which represents more than 14 times the world demand for hydrogen in 2018.

Figure 12 - 10: Schematic of estimating the technical potential of hydrogen production in Brazil



It considers the PNE 2050 Scenario of Expansion Challenge and that all of the domestic electricity demand is supplied with renewable onshore energy resources.

Source: Prepared by EPE.

Table 12 - 6 shows the result of the estimate of the annualized technical potential of hydrogen production from the balance of energy resources in the 2050 timeframe.

Table 12 - 6: Estimation of the technical potential of hydrogen production from the energy resources until 2050

Energy Resource	Hydrogen Potential in Mt/year
Renewable – Offshore*	1,715.3
Renewable – Onshore*	18.1**
Biomass	50.5
Nuclear	6.9
Fossil fuels	60.2
Total	**1,851**

Notes:
* Onshore and offshore renewable resources considered are hydro, solar and wind power.
** The potential may prove to be much higher, because the real energy mix of the power system is more diverse in technologies.
Source: Prepared by EPE.

Offshore renewable resources stand out with enormous technical potential for hydrogen production. The resource with the largest share is solar photovoltaic with 79% of potential, followed by wind power, in addition to the 100 km up to the limit of the Exclusive Economic Zone (ZEE), which is 15%. The remaining wind resource up to 100 km off the coast has a potential of 101.2 Mt H2/year and from the ocean energy, 8.8 Mt H2/year. These values are shown in **Table 12 - 7**.

Table 12 - 7: Detailing the technical potential of hydrogen production from offshore renewable resources

Offshore Renewable Energy Resource	Hydrogen Potential in Mt/year
Wind Offshore - 10 km dist.	11.2
Wind Offshore - 50 km (exc. 10 km dist.)	39.8
Wind Offshore - 100 km (exc. 50 km dist.)	50.2
Wind offshore - ZEE (exc. 100 km dist.)	249.2
Oceanic	8.8
PV Offshore	1,356.1
Total	1,715.3

In 2020, EPE published the study “Roadmap Wind Offshore Brazil” where it mapped the resource to towers of 100 m in height and at a bathymetry (sea depth) of up to 50 m (EPE, 2020). The total offshore wind resource in this condition was 218 Mtep, which converted to hydrogen is equivalent to 56.4 Mt.

After the conclusion of the PNE 2050 energy resource inventory studies, studies on the occurrence of geological hydrogen (natural hydrogen) in the country began to emerge. Although scientific knowledge about this resource is still very limited in the world, its renewable, clean nature and, potentially, very low costs motivate further investigations, which can expand the resource base.

Furthermore, some experts expect hydrogen produced by electrolysis of water using electricity generated from renewable sources such as hydro, wind and solar to be competitive by 2030.

While the dispute of gray and blue versus green hydrogen has dominated the debate, there is a wide range of alternatives to building a hydrogen economy. In this way, several other technological routes may also have important roles to play in the low-carbon hydrogen industry.

The development of the renewable hydrogen market will benefit from synergy with the low or zero carbon hydrogen market (such as blue, turquoise and pink hydrogen), as has been pursued in the US, Canada and Norway. Even Germany, which focuses its strategy on green hydrogen, will temporarily accept blue and turquoise hydrogen to contribute to market development and ensure more competitive prices in the early stages.

Regarding renewable and carbon-free hydrogen, it will play three key roles in the energy transition: i) decarbonize segments that are difficult to abate emissions, such as the long-haul heavy transport sector (trucks, trains and vessels), the airline and industry (fertilizers, steel and cement, for example); ii) facilitate the storage of energy from variable renewable sources such as wind and solar; and, iii) allow coupling between the electricity, transport and industrial markets.

As far as green hydrogen is concerned, the development of domestic and foreign markets will be important to gain scale. And while green hydrogen is an important part of the whole process, other types of low- and zero-carbon hydrogen will also play an important role.

Box 12 - 3: Natural hydrogen in Brazil

As for natural hydrogen, previously considered marginal, if not non-existent, it increasingly appears as an important option to be explored by energy companies in the near future (Prinzhofer & Deville, 2015; Deville & Prinzhofer; 2015; Zgonnik, 2020). Many startups are launching exploration/production programs in various countries around the world, while large energy companies and governments are watching and acting more discreetly but insistently.

The known sources of natural or geological H_2 are: 1) radiolysis, related to the natural radioactivity of rocks, which, in particular, separates hydrogen and oxygen from water, releasing these gases; 2) the oxidation of iron minerals (Fe), with Fe^{+2} oxidizing to Fe^{+3} generating magnetite, hematite, biotite, etc., and with the reduction of water releasing H_2; 3) the action of sulfur (S), which with the reduction of Fe^{+3} to Fe^{+2}, generating pyrite (H_2S) and H_2; and, 4) the decomposition of the ammonia ion NH_4^+ which will decompose into N_2 and H_2 (PRINZHOFER et al., 2019).

In terrestrial environments of cratonic geological terrains of Proterozoic age, hydrogen has also been observed in the United States (South Carolina, Kansas), Canada, Australia, Brazil, and many other places. The source is relatively similar: oxidation of an iron-rich material and release of H_2, these surface exudates are systematically in very ancient regions, usually Proterozoic or Neoproterozoic, and rich in metals (MORETTI et al., 2018).

Mali, located in the western part of Africa, is currently the largest example of hydrogen exploration and production in the world. Mali is the only example of industrial production of natural hydrogen in the world, with hydrogen occurring in reservoirs at depths between 100 m and 1,800 m. The gas produced is currently used to generate clean energy and public lighting for an area of the village of Bourakébougou, near the capital Bamako, in a poor rural area that had no access to electricity (PRINZHOFER, CISSÉ and DIALLO, 2018).

In this context, it is observed that Brazil is a country of enormous territorial extension and encompasses several Proterozoic and Mesoproteozoic cratonic zones that, as mentioned above, are conducive to the generation and preservation of natural hydrogen. Preliminary exploratory campaigns carried out in several states of the federation showed significant potentials in hydrogen. Areas were studied in the states of Ceara, Goiás, Tocantins, Roraima, Minas Gerais and Bahia that presented different potentials for natural hydrogen research. Some better and some worse, but always positive. This list is not exhaustive, as many other regions have never been studied.

Some areas of Brazil have already been explored for natural hydrogen. This work was initially carried out in partnership with the State University of Rio de Janeiro (UERJ) and later with the company Engie Brasil, which sponsored a more extensive work with excellent results. Several areas showed the presence of hydrogen in the soil, and deep wells in the São Francisco Basin found high concentrations of hydrogen in deep reservoirs, thus indicating the existence of active hydrogen systems in these regions.

Box 12 - 3: Natural hydrogen in Brazil

Despite these initial studies, the potential of this resource in Brazil is still unknown. However, MORETTI et al. (2021) estimate an emission of 140 t/day (51.1 kt/year) of hydrogen, in three areas identified in the São Francisco Basin, indicating that the hydrogen production potential indicated in the present study can be considered as optimistic.

Thus, in order to achieve the goal of decarbonizing the world economy, we must not choose just one path, as we will need all the alternatives that contribute to decarbonizing the world energy mix, through a path of fair and economically sustainable energy transition.

12.3.1 POTENTIAL MARKET

Brazil has great opportunities to take advantage of its renewables in the green hydrogen and zero or low carbon industry in general. Good positioning for export to developed markets and potential demand in fertilizers (green ammonia), production of advanced biofuels (HVO and biokerosene via HEFA route), energy storage for electrical generation from variable sources, fuel cell for light and heavy transport, green steel (H_2 for direct reduction in the steel industry) and green methanol for biodiesel production (today methanol is totally imported).

Despite being heavily dependent on imports to meet its demand for fertilizers, Brazil has a strong agribusiness industry. Therefore, it is a great opportunity to produce hydrogen for fertilizers in Brazil, which could benefit from the National Fertilizer Plan. The same goes for ore, steel and other metals. Brazil produces and exports ore, steel and other metals, and these materials, with green certifications, could be premium products in the global commodity market in the coming decades.

Considering that the Paris Agreement changes the global market to a context of increasing demand for cleaner products, markets for hydrogen in the mining, steel, metals and fertilizer industries, among others, must be developed. Additionally, green hydrogen projects in Brazil should be built in ports that have industrial districts and have plans to produce green ammonia and other green commodities for domestic and international markets, creating important synergy and developing new competitive advantages for the country.

According to long-term forecasts on the global consumption of pure hydrogen, there is an expectation of sustained growth, from 73 million tonnes in 2018, to values around 200 and 500 million tonnes in 2050, depending on the implementation of carbon dioxide emission reduction policies in the world (IEA, 2021).

In this context, Brazil could become a major exporter of hydrogen in the future, being a very competitive country in renewable sources, with significant water resources (including extensive access to the sea and desalination technology, as well as great potential for water reuse), robust infrastructure, including logistics and ports, with a large and modern energy sector, as well as national human capital to develop an important hydrogen market and export to the global market, taking advantage of its distance to the main developed markets.

However, to take advantage of the opportunities, it will be necessary to invest in R&DI, especially to reduce costs such as those of green hydrogen products, for example, as they are not yet competitive with similar ones of fossil origin. New end-use technologies also need to be improved and/or developed. Hence, the importance of CNPE Resolution No. 2/2021, which identifies hydrogen as one of the priority issues for the allocation of resources in the ANEEL and ANP R&DI programs. The country should also become very competitive in natural gas after the consolidation of the reforms promoted by the New Gas Market. And, therefore, the country has invested in R&DI both in the steam reform of natural gas and ethanol and in the electrolysis of water based on hydroelectric, wind and solar energy. CNPE Resolution No. 2/2021 and PNH2 will reinforce this strategy.

It should be noted that, even with modest volumes, pilot projects in the scope of R&DI (Research, Development and Innovation) of energy storage can have a very significant long-term impact for the greater insertion of variable renewables in the electricity mix in Brazil. In particular, mention should be made of the hydrogen production projects for energy storage at the Itaipu Technological Park, by Hytron for the BAESA and ENERCAN companies and, more recently, the aforementioned Furnas project at the Itumbiara Hydroelectric Power Plant (hydroelectric-solar photovoltaic – hydrogen).

On the other hand, hydrogen from ethanol, for example, could play a fundamental role in the Brazilian automotive market and in other sugar and ethanol producing countries in the future (such as India, for example). Some automakers present developments, testing prototypes of fuel cell electric vehicles with hydrogen from onboard reform of ethanol or from distribued hydrogen production in gas stations. This means that most of the infrastructure is already available in Brazil, with little investment needed to overhaul the infrastructure. Still, synthetic fuels from other hydrogen routes will also play an important role.

In 2021, in addition to several pilot-scale R&D projects, several industrial-scale green hydrogen projects were announced: the State of Ceará Green Hydrogen Hub at Pecém port; projects in the State of Pernambuco at Suape Port; and projects in the State of Rio de Janeiro at Açu Port. These projects are undergoing technical and economic feasibility studies.

Table 12 - 8 summarizes the low-carbon hydrogen projects announced in Brazil in 2021, as well as their characteristics, when available.

Table 12 - 8: H_2 projects in Brazil

Project	Company	Location	Scale	Stage
Purification of H_2	Electronuclear	Angra I and II, State of Rio de Janeiro	150-300 kg H_2/d	R&D
Green H_2	PTI	Pecém port, State of Ceará	Pilot	R&D
Green H_2 from UHE and PV	Furnas	Itumbiara, State of Goiás	Pilot	R&D
Steam Reforming of bioCH_4 to produce Green H_2 and Green NH_3	Yara with CH_4 from Raízen	State of São Paulo	20,000 m^3/d	Commercial in 2023
Green H_2 in public transportation	Neoenergy	State of Ceará		MoU
Fertilizer (Green NH_3)	Unigel	Camaçari, State of Bahia	Commercial	Conversion in late 2022

Project	Company	Location	Scale	Stage
Green H_2 and Green NH_3 from Wind	Enterprize Energy	State of Rio Grande do Norte	Commercial	MoU
Green H_2	Fortescue	Açu port, State of Rio de Janeiro	Commercial (300 MW and 250 kt NH_3)	MoU
Green H_2	Fortescue	Pecém port, State of Ceará	Commercial	MoU
	Enegix		Commercial (600 kt NH_2)	MoU
	Qair		Commercial (540 MW)	MoU
	White Martins (Linde/Praxair)		Commercial	MoU
	EDP		Commercial (250 m^3 NH_2/h)	MoU
Blue and Green H_2	Qair	Suape port, State of Pernambuco	Commercial (540 MW)	MoU
Green H_2	Neoenergy	State of Pernambuco	Pilot	MoU

12.4 Opportunities and Challenges

Hydrogen is not a new source and still faces some challenges. Nevertheless, the current moment drives low carbon hydrogen, which promises to become a relevant source and storage of energy and to promote the coupling of the energy market with the industry and transport sectors in the coming decades.

The acceleration of hydrogen market development results in a wide range of business opportunities. There are different technological routes and inputs for the production of hydrogen, providing opportunities for the oil and gas, renewables, biofuels, nuclear, electrical and other energy industries. On the other hand, cost-competitive hydrogen can be used for different economic activities such as transportation, power generation, energy storage, fertilizers, steel mills, refining and biorefining, including obtaining advanced biofuels such as HVO and biokerosene, as well as in other chemicals etc. In addition, there is a developing global hydrogen market, mainly based on green, blue and turquoise hydrogen.

As discussed in chapter 3 (Centralized Electricity Generation) of this PDE, the competitiveness of domestic hydrogen will have a direct impact on the energy sector as a whole, affecting the demand for inputs. In the specific case of the electricity sector, the impact is expected both on the demand for electricity, to be used in electrolysers, for example, and on the expansion of generation, to serve these consumers, with emphasis on renewable sources, with consequent impact in expanding the transmission network. This competitiveness, in turn, is directly linked to the price of electricity in the case of electrolysis, which can represent about 70% of the cost of producing hydrogen, which represents an opportunity for the country, given the availability and low cost of renewable generation, when compared to other markets.

To take advantage of opportunities, first of all, institutional, legal and regulatory structures must be improved, adapting them to provide stability, predictability and confidence to investors. Furthermore, to reduce information asymmetry about energy resource availability and costs, capital and operating costs of projects, as well as potential market and human capital, the business environment must be improved. The Hydrogen Energy Pact, presented by Brazil at the UN High Level Dialogues on Energy, aims to provide information and publicize opportunities to attract investments to Brazil. The importance of competitiveness and support for innovations related to hydrogen is also highlighted, as already discussed, reinforcing the need to establish international cooperation among countries with convergent interests and that seek mutual benefits.

In this context, it is important to highlight the need to identify taxation and financing constraints, as well as the need to improve conditions for attracting investments in low-carbon hydrogen. And, additionally, advance in the identification of market potential and issues related to demand.

In addition to exports, the main uses and opportunities for Brazil and the rest of Latin America (there are relevant synergies that can be taken advantage of) are: fertilizers, energy storage to allow greater insertion of variable renewables in the electrical mix, hydroprocessing of vegetable oils to make advanced biofuels like HVO, jet biokerosene and biobunker and use of fuel cells in vehicles and equipments (such as industrial forklifts). In the case of Brazil, large machines in mining, steel and heavy trucks, as well as fuel cell vehicles with ethanol will also be opportunities in the longer term (or when there is competition).

There are technological and cost challenges in hydrogen infrastructure, which require special metallurgy solutions for pipelines and tanks and which are more expensive than conventional infrastructure. In addition to these, there are still challenges related to terminology (colors or associated carbon content), clarity on the principle of additionality and the need for standards for certification of origin. Furthermore, the hydrogen production costs themselves are a challenge to its competitiveness. In particular, for green and low-carbon hydrogen, which requires knowledge of the potential of each route.

Finally, it must be considered that Brazil will not only be a supplier of green commodities, but also a competitive hydrogen economy that will produce, including for export, minerals, steel, metals, ammonia, agricultural commodities and other low-cost or zero carbon industrial goods and services.

MAJOR POINTS OF THE CHAPTER
HYDROGEN

- *According to the International Energy Agency, in 2018, the world demand for hydrogen was 115 Mt, with 73 Mt of pure hydrogen.*
- *In Brazil, the demand for hydrogen reached around 1 Mt, 50% for fertilizers, 37% for refining, 8% for chemicals and 4% for metallurgy/food, with 95% of fossil origin (predominantly natural gas).*
- *The estimated annual production of hydrogen from the estimated surplus of energy resources for hydrogen production in the timeframe of 2050 is of the order of 1,850 Mt/year, with offshore renewable resources standing out with an enormous technical potential for hydrogen production.*
- *Bearing in mind the importance of an inclusive approach and flexible paths for the energy transition, avoiding technological lock-ins and taking advantage of its potential, Brazil has great opportunities with the hydrogen economy, both in the domestic and foreign markets, with the developments associated with the National Hydrogen Program being strategic.*

Appendix B: Hydrogen

Table B-1- Energy resources used in the calculation basis of hydrogen potential in the 2020 to 2050, on an annual basis.

Energy Resource	PNE 2050 Inventory (Mtep/year)	Period
Renewables	**7,215**	
Biomass	375	Amount in 2050
Wind	1,386	Continuous Flow
Water	108	Continuous Flow
Solar	5,347	Continuous Flow
Non-Renewable Fossil Fuels	**610**	
Steam coal	239	Average between 2020 and 2050
Natural Gas	94	Average between 2020 and 2050
Oil	277	Average between 2020 and 2050
Non-Renewables Nuclear	**80**	
Uranium	80	Average between 2020 and 2050
Grand Total	7,905	

Source: Prepared from EPE, 2018 - PNE 2050 Technical Note on Energy Resources.

Table B-2 - Accumulated final demand of energy sources that impact the availability of resources for hydrogen production, until 2050.

End Sources	End Demand (Mtep)	Period
Electricity	134	Amount in 2050
Steam coal	195	2020 to 2050 to date
Natural Gas	1,073	2020 to 2050 to date
Oil Products	5,381	2020 to 2050 to date
Total	6,783	-

Source: EPE.

Table B-3 - Balance of energy resources with potential for producing hydrogen in the 2050 timeframe.

Energy Resources	Balance with Hydrogen Potential (Mtep/y)	Period
Non Renewable - Fossil Fuel	388	Average between 2020 and 2050
Steam coal	232	Average between 2020 and 2050
Oil	98	Average between 2020 and 2050
Natural Gas	58	Average between 2020 and 2050
Non-Renewable Nuclear	80	Average between 2020 and 2050
Renewable – Offshore*	6,637	Continuous Flow
Renewable – Biomass	372	Continuous Flow
Renewable – Onshore*	70	Continuous Flow
Total	7,547	-

* Onshore and offshore renewable resources considered are hydro, solar and wind power.

The technological routes adopted in this estimate, for the conversion of energy resources into hydrogen, are presented in the Table below. In the cases of Sugarcane Bagasse and Natural Gas, routes with greater value of conversion into hydrogen were adopted.

Table B-4 - Conversion factors of energy resources into hydrogen.

Energy Resource	Hydrogen Production Potential	Conversion Factor (tH_2/tep)
Hydro, Wind and Solar	Electrolysis	0.258
Forest Biomass and Agricultural Waste	Biomass gasification	0.130
Sugarcane Bagasse	Biomass gasification	0.130
	UTE + Electrolysis	0.059
	Anaerobic Biodigestion + Vapor Renovation (Decentralized)	0.036
Farming Waste	Anaerobic Biodigestion + Vapor Renovation (Decentralized)	0.210
Nuclear	UTN + Electrolysis	0.086
Natural Gas	Vapor Renovation (Centralized)	0.227

Source: Prepared by EPE.

Although the conversion factor to hydrogen from Natural Gas via centralized steam reforming is higher than the decentralized option, the existing structure for moving this energy source, the greater simplicity in transport in relation to hydrogen and the possibility of conversion at consumption points, can make the decentralized option more attractive. Furthermore, the development of methane pyrolysis technology can contribute to the mitigation of CO2 emissions, since the carbon of the methane molecule after pyrolysis constitutes a solid product, which can be used in other processes or sequestered.