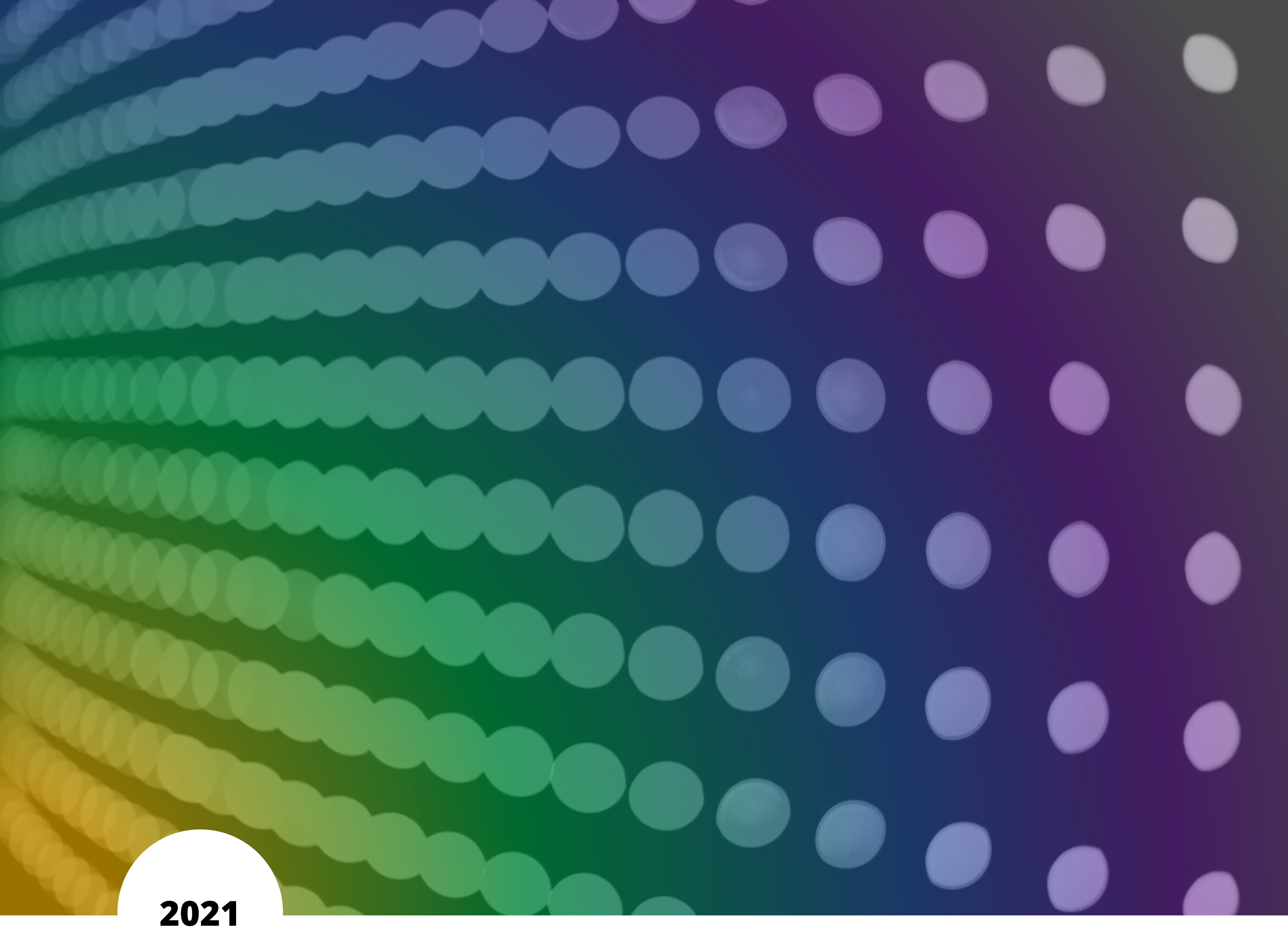

2021

Baseline to support the Brazilian Hydrogen Strategy

Empresa de Pesquisa Energética

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President
Thiago Vasconcellos Barral Ferreira

Director for Energy Economics and Environmental Studies
Giovani Vitória Machado

Director for the Electricity Studies Division
Erik Eduardo Rego

Director for the Oil, Gas and Biofuels Studies Division
Heloísa Borges Esteves

Director for Corporate Management
Angela Regina Livino de Carvalho

URL: http://www.epe.gov.br

Head Office
Esplanada dos MInistérios - Bloco U
Ministry of Mines and Energy - Room 744 - 7th floor
70065-900- Brasília – DF
Central Office
54, Praça Pio X, Centro
20091-040 - Rio de Janeiro – RJ

TECHNICAL NOTE

Baseline to support the Brazilian Hydrogen Strategy

General Coordination
Thiago Vasconcellos Barral Ferreira

Executive Coordination
Giovani Vitória Machado

Director's Advisory
Jeferson Borghetti Soares

Head of Department
Carla Achão
Elisângela Medeiros de Almeida

Deputy Head of Department
Glauce Maria Lieggio Botelho
Gustavo Naciff de Andrade

Technical Team
Gustavo Pires da Ponte
Luciano Basto Oliveira
Marcelo Costa Almeida
Mariana Lucas Barroso
Rodrigo Vellardo Guimarães

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Index

1 Introduction

After decades of being known as the most potential and disruptive energy carrier for the future, despite technological and market challenges, hydrogen has become a strategic topic for governments and companies worldwide. In particular, the hydrogen market will gain momentum from post-pandemic energy policies for economic recovery and to accelerate the energy transition in several countries.

Hydrogen has already a relevant market size. In 2019, hydrogen's global market achieved from USD 118 billion (GRAND VIEW RESEARCH, 2020) to USD 136 billion (MARKETS AND MARKETS, 2020). Moreover, projections anticipate significant market growth in the coming years, which could reach amounts of USD 160 billion (GLOBAL MARKET INSIGHTS, 2020) to almost USD 200 billion (MARKETS AND MARKETS, 2020). The driving force behind this growth is the perspective of governments and companies on the role of hydrogen in enabling deep decarbonization in the economy, required to achieve the Paris Agreement goals by 2050.

Beyond traditional markets, like fertilizers, oil refining, and others (industrial and hospital gases), new hydrogen markets may be developed in transportation, electricity generation, energy storage and industrial processes, among others.

Hydrogen can be used directly as a low or zero carbon energy source (depending on its production process) in sectors that are difficult to electrify. It also can be used for energy storage, enabling greater entry of variables renewable such as wind, solar, etc. Therefore, hydrogen is seen as a resource capable of enable sector coupling (fuel, electric, industrial, and other markets).

This Technical Note aims to address important conceptual and fundamental aspects to support the Brazilian hydrogen strategy. This Note has the following main sections: hydrogen market overview; technological routes and processes of hydrogen; cost and competitiveness of hydrogen; challenges for market development of hydrogen energy use; hydrogen role in energy transition; and final remarks.

2 Hydrogen market overview

In 2018, demand for hydrogen was 115 Mt, 73 Mt of it in its pure form (IEA, 2019a). Ammonia production for use as fertilizer and oil refining consumed 96% of pure hydrogen. In addition, demand for hydrogen mixed with other gases was 42 Mt, 29% of this related to methanol production, 7% to direct reduced iron steel production, and the remaining to other uses. Figure 1 shows the historical global demand for pure and mixed hydrogen.

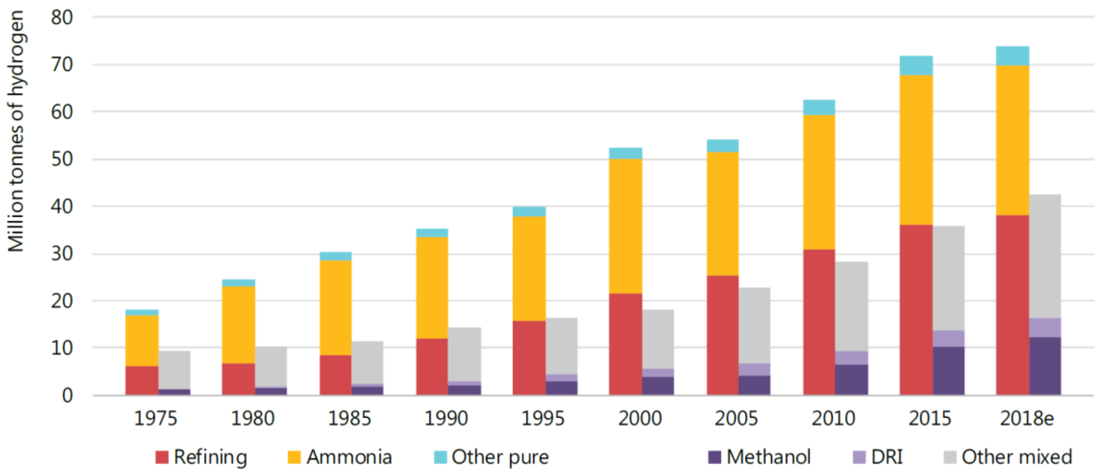


Figure 1 – Global demand for pure and mixed hydrogen
Fonte: IEA (2019a)

Ammonia (NH_3) is important to fertilizers production. Its main production process, known as Haber-Bosch process, usually uses nitrogen from air and hydrogen from steam methane reform.

In oil refining, hydrogen is used not only to hydrocracking of heavy oils to obtain higher yields of most valuable oil products (light and medium), but also to hydrotreat products to achieve fuel quality standards (mainly sulfur, oxygen, and metals removal). Refineries' hydrogen demand has growth over the last decades due to i) fuel oil production reduction goals (market loss to natural gas) and to "recover" higher amounts of light and medium oil products (gasoline, diesel and jet fuel market growth), and ii) environmental and quality fuel regulations restrictions for local pollutants emissions (SOx, NOx, and metals) that forced refineries to increase oil products quality through contaminant removal.

Hydrogen supply profile for refineries varies by region, as shown in Figure 2. It could be supplied by hydrocracking units, as byproduct, or by on-site steam methane reformer (SMR).

Coal gasification is also used to produce hydrogen, mostly on Chinese refineries. This process is also important to Australia, that even exports hydrogen to Japan.

Merchant supply for refineries is also relevant globally, particularly in the US.

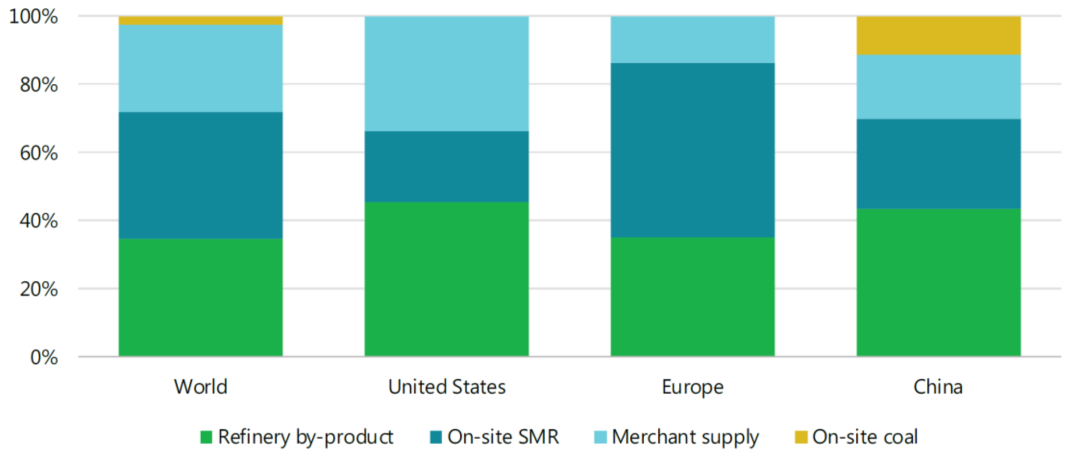


Figure 2 – Hydrogen supply for refineries in 2018
Note: SMR (Steam Methane Reforming)
Source: IEA (2019a)

The Merchant Market shows that there are qualified suppliers to answer to any new market, not only self-producers. The current Merchant installed capacity is 8,6 Mt/year and its division by region is shown in Figure 3.

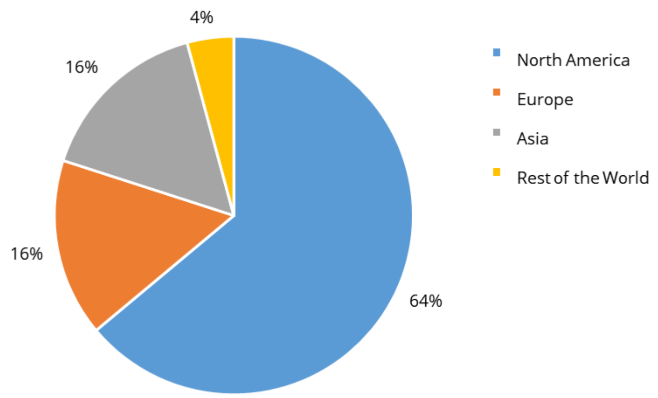


Figure 3 – Merchant installed capacity *to hydrogen production worldwide*
Note: Data from November of 2015 to Europe and January of 2016 to the rest of the world
Source: Adapted from PNNL (2020a)

The US is the greater merchant producer with 58% of world installed capacity. In addition, Canada and China have the same percentage, 6% each, and Germany has 4% of world installed capacity. The main companies are Air Products (36%), Praxair (21%), Air Liquide (21%), and Linde (13%) (PNNL, 2020a).

Regarding hydrogen production technological route, steam methane reform is the major technology with 75% of world installed capacity. The delivery state of hydrogen to end users is mostly gaseous (83%). Compressed hydrogen delivery accounts for 16% in the world (PNNL, 2020a).

It is worth noting that there is already an international hydrogen market in place, although it represents less than 10% of the total hydrogen market size. In 2017, according to the *Observatory of Economic Complexity* (OEC, 2020), the international hydrogen Market transacted around USD 11,75 billion. The biggest exporter were US (USD 2,22 billion), China (USD 1,75 billion), Germany (USD 1,33 billion), South Korea (USD 1,29 billion), and Norway (USD 580 million). The biggest importers were China (USD 2,78 billion), Japan (USD 1,71 billion), Germany (USD 921 million), South Korea (USD 789 million) and then other Asian countries (USD 800 million). Brazil achieved USD 335 million from exports and USD 61 million from imports.

Due to hydrogen market expectations for energy purpose, the international market could also have a significant increase. The European Union and Germany have already announced investments policies in hydrogen plants over other countries aiming the development of world market for hydrogen for energy purposes.

Lastly, it should be noted that the energy use of hydrogen is still very limited. There are many reasons for that, such as technological challenges to produce low carbon hydrogen, production costs, equipment cost to hydrogen energy use (including safety aspects), storage and transport difficulties, the need to develop institutional, legal, and regulatory frameworks (market design, standardization, etc.), among others.

3 Technological routes and processes of hydrogen production

Hydrogen can be produced from various raw materials and technological routes, as well as from direct extraction from natural occurrences (geological). Figure 4 shows a simplified scheme of the technological routes, from hydrogen production to its final use.

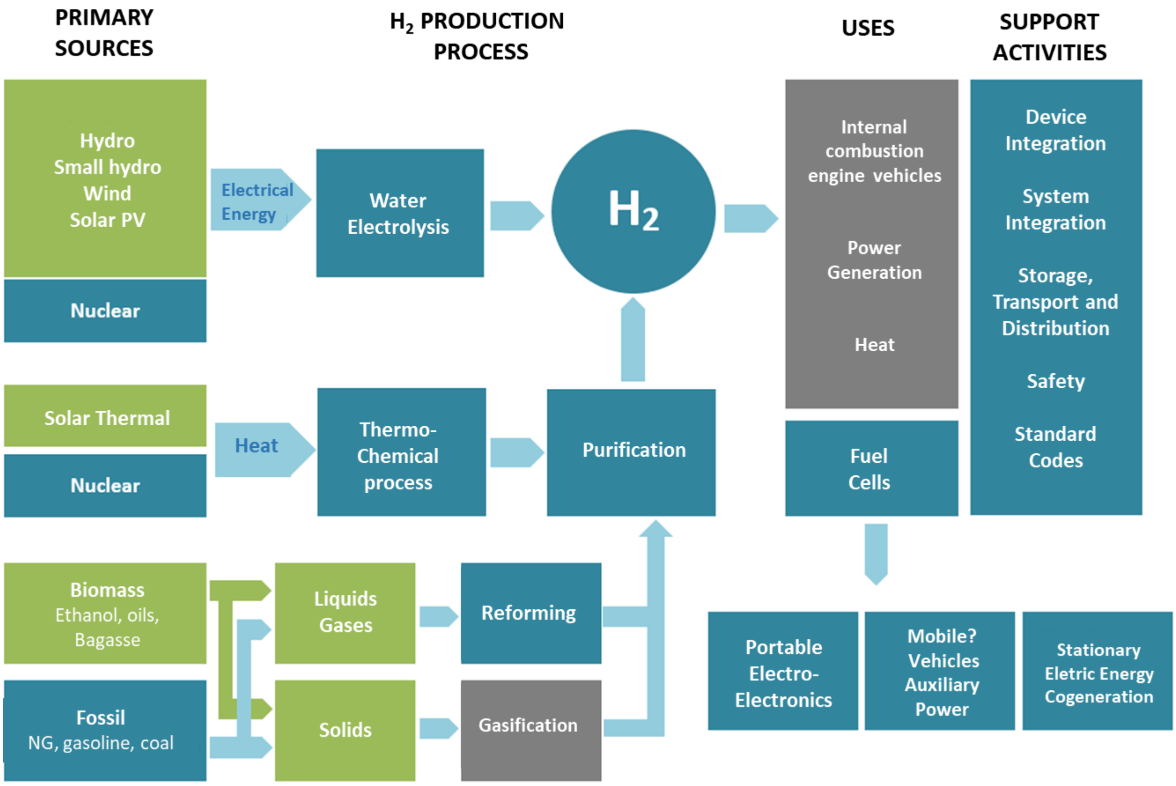


Figure 4 – Technological routes for hydrogen production

Source: Elaborated based on CGEE (2010)

Water, biomass, and biofuels (ethanol, biogas etc.) are the renewable sources used for hydrogen production.

Hydrogen production from water is made via electrolysis. The electricity consumed in the process can be generated from renewable sources (e.g. wind, solar or hydro) resulting in a carbon free or low carbon hydrogen. Currently, two electrolysis technologies are employed: The Alkaline and the Polymer Electrolyte Membrane (PEM).

Thermochemical Cycles (TC) can also be used to split water molecules and produce hydrogen. This technology requires high temperatures and the use of intermediary substances that can be regenerated. Concentrated Solar and Nuclear Reactors are candidates to be the source of heat to TC processes. However, TC technologies are still under development (IAEA, 2013; GUBAN et al. 2020).

Biomass and biofuels conversion to hydrogen is made via steam reforming, gasification, or biological processes. The gasification of biomass is not as straightforward as of coal, because of lower energy and moist content. However, the process is technically viable and was used in cars in the past. Syngas from gasification contains not only hydrogen, but also carbon monoxide. If pure hydrogen is required, then a separation process should be used.

Biofuel reform is another option for hydrogen production. In particular, the steam reform of ethanol is well developed. This is a relevant option for the transport sector, as it avoids the difficulties associated with hydrogen storage (MARIN NETO et al., 2004).

Among biological processes, biodigestion can provide methane to be reformed, as with natural gas, or be controlled to avoid methanogenesis, in whole or in part, and provide hydrogen (SILVA et al, 2017).

Gasification and reform can also be applied to non-renewable sources carrying hydrogen. The gasification of coal and, mainly, methane reform are mainly used to serve refineries, fertilizer, and methanol production. As a relevant data, currently in the world, the dedicated production of hydrogen is 70 Mt per year, being 76% from natural gas and 23% from coal. Water electrolysis accounts for less than 0.1% of dedicated production. However, also considering the production of hydrogen as a co-product, electrolysis in the chloralkali process accounts for about 2% of the total global hydrogen production (IEA, 2019a).

In addition to the technological routes of obtaining hydrogen mentioned above, it is also worth mentioning the discovery of natural hydrogen geological reservoirs in Mali (PRINZHOFER et al., 2018). In nature, several natural processes can result in the geological production of hydrogen, including water radiolysis, serpentinization and iron ore oxidation (ZGONNIK, 2020). Although there is already an important scientific literature on the subject, this option is still little known and discussed regarding its economic use in the market.

A very rich description of the various hydrogen production processes can be accessed in IAEA (2013), HOU et al. (2015), LÓPEZ et al. (2013), PARNELL & BLAMEY (2017), SILVA (2017) and CGEE (2010). These routes, in turn, are distinguished in terms of their conversion efficiency into hydrogen, and the values for the main hydrogen production processes are presented in Figure 5.

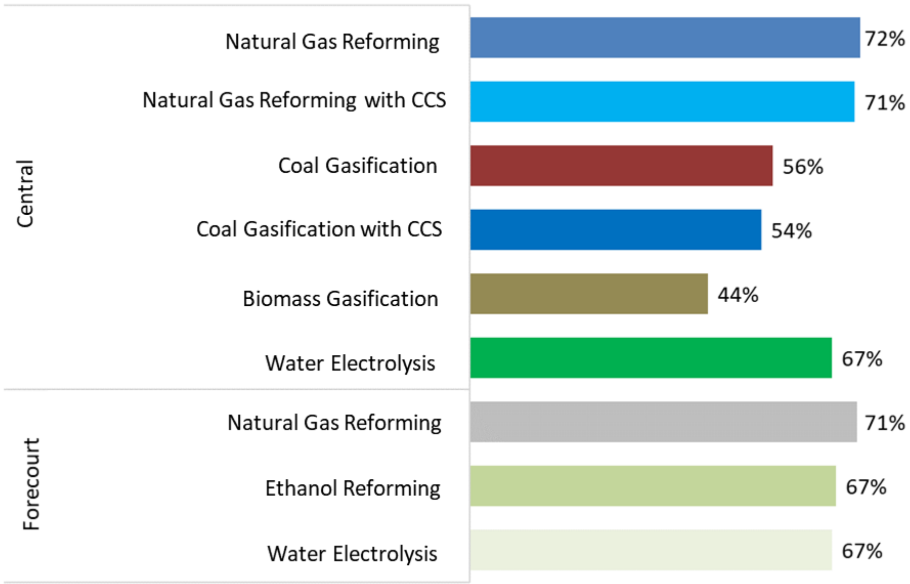


Figure 5 - Typical conversion efficiencies into hydrogen production processes
Source: PNNL (2020b)

Another important aspect to be mentioned is that in the context of the global concern with the decarbonization of energy production and consumption systems, its transformation with hydrogen as the main energy vector has led to the search for differentiation of hydrogen according to its origin, as well as the possible coupling or not of carbon capture technologies (CCUS) to these hydrogen production processes. The differentiation of technological routes of hydrogen production, according to the carbon footprint, seeks to couple the differential by environmental quality, enabling the existence of a "premium" price. It could be cited, as a similar example, electricity, whose use is independent of the source of generation, but whose differentiation (economic) can occur when considering the origin of its production as an attribute for public policy purposes (e.g., reduction of greenhouse gas emissions) and also pricing in the electricity market.

In turn, the differentiation of hydrogen product, by carbon footprint associated with its production, has different implications in terms of contributions to the mitigation of greenhouse gas emissions and prevention of global climate change. In this context, although from a technical point of view it may be more appropriate to differentiate hydrogen through an index that reflects the carbon footprint associated with its production, it has currently been sought to differentiate this origin of production by colour terminology (IEA, 2019a):

- "Brown or black hydrogen" is produced from coal (of lignite is the "brown" and of coal or anthracite corresponds to the color "black") without CCUS (capture, use and sequestration of carbon).
- "Gray hydrogen" is produced from natural gas without CCUS.

- "Blue hydrogen" refers to its production from natural gas, but with CCUS (eventually, this name is also used for hydrogen generated from other fossil fuels with CCUS).
- "Green hydrogen" has been defined, in market jargon, as hydrogen produced via electrolysis of water with energy from variable renewable sources (particularly wind and solar energy).

Considering that the classification of hydrogen in colors presents different definitions depending on the reference, it is emphasized that hydrogen obtained by other renewable routes has not been included in the concept of "green hydrogen" such as electrolysis of water from hydropower and pyrolysis, gasification of biodigestion of biomass or plastic waste of end-of-life. The same is the case with hydrogen generated by routes with zero carbon emissions such as nuclear energy. There are also mentions of other colors such as white, referring to natural or geological hydrogen, and turquoise, obtained by thermal cracking of methane, without generating CO_2 (H2-VIEW, 2020; BAKER MCKENZIE, 2020; ZGONNIK, 2020). However, the criteria are not always the same and different publications often use certain colors to designate hydrogen obtained by different processes. Germany, in its National Strategy, defines Turquoise Hydrogen as the thermal cracking of methane route, generating C(s) and not $CO_{2,}$ only if the heat source is carbon neutral (GERMANY, 2020).

Until the time of the preparation of this document, no definitive and robust label taxonomy for hydrogen produced by other different technological routes has been identified in the literature, nor market jargon for all routes defined above. On the contrary, IEA (2019a) questions the technical rigor of using colors to define hydrogen by technological routes. Nevertheless, to facilitate the reference to other routes and use the common 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 biodigestion to moss color (with variations of shades of green that can go from "brownish", case of significant changes in soil use, to "greenish", case of null or negative carbon).

Considering the aspects outlined above, table 1 below presents the summary of the classification of hydrogen on a color scale.

Table 1 – Color scale for hydrogen classification

Color	***Classification***	***Description***
	Black Hydrogen	Produced by gasification of coal (anthracite), without CCUS
	Brown Hydrogen	Produced by gasification of coal (coal), without CCUS

■	Gray Hydrogen	Produced by steam reform of natural gas, without CCUS
■	Blue Hydrogen	Produced by steam reform of natural gas (possibly also from other fossil fuels), with CCUS
■	Green Hydrogen	Produced by electrolysis of water with energy from renewable sources (particularly wind and solar energy).
□	White Hydrogen	Produced by natural hydrogen extraction or geological.
■	Turquoise Hydrogen	Produced by thermal cracking of methane, without generating CO_2
■	Moss Hydrogen	Produced by catalytic reforms, gasification of plastics at end-of-life to syngas, anaerobic biodigestion of biomass or biofuels, with or without CCUS
■	Pink	Produced by nuclear power source

Source: Prepared from IEA (2019a), H2-VIEW (2020), BAKER MCKENZIE (2020) and ZGONNIK (2020).

4 Cost and competitiveness of hydrogen

Hydrogen Market has achieved a new momentum with several governments' announcements of its strategic plan for hydrogen development and its important role in supporting energy transition. The main reasons are the advantages of hydrogen such as high energy density, versatility, carbon-free fuel, and the fact that it could work as an energy storage option.

Several initiatives have been put in place to make green hydrogen economically feasible. There are two main goals: economy recovery and support energy transition in hard-to-abate sectors, for example transport, aviation, shipping, iron and steel industry, fertilizers, among others.

The EU and Germany have launched strong strategies for the development of green hydrogen market and to speed cost reductions. However, cost and competitiveness data denote that there is a strategic choice for market development:

- On the one hand, steam methane reforming (gray hydrogen) is the technological route that would make new markets easier to develop because it is the dominant technology and the most competitive. However, this route could face risks in the future due to restrictions in a scenario of deep decarbonization (stranded assets) and a rapid cost reduction of renewable-based water electrolysis (green hydrogen).
- On the other hand, green hydrogen route is still not very competitive. Nonetheless, this route could have good opportunities in the future in a scenario of great cost reduction on electrolysis and production of electricity from renewables (wind and solar, mainly). The deep decarbonization commitments of economies contribute to this scenario.

Indeed, the lowest hydrogen production costs are currently observed in the steam methane reforming (natural gas) and in coal gasification, technological routes based on fossil fuels. Water electrolysis using renewable electricity (wind and solar) is, in general, the most expensive technological route among those already commercially available. Obviously, there are certain special conditions and geographical advantages that could make some projects competitive today, exploring specific niches.

Figure 6 shows hydrogen production costs range for some technological routes based on literature review. It is worth noting that hydrogen production cost from ethanol reforming is already competitive with the use of hydrogen in vehicle refueling stations (MORAES et al., 2019).

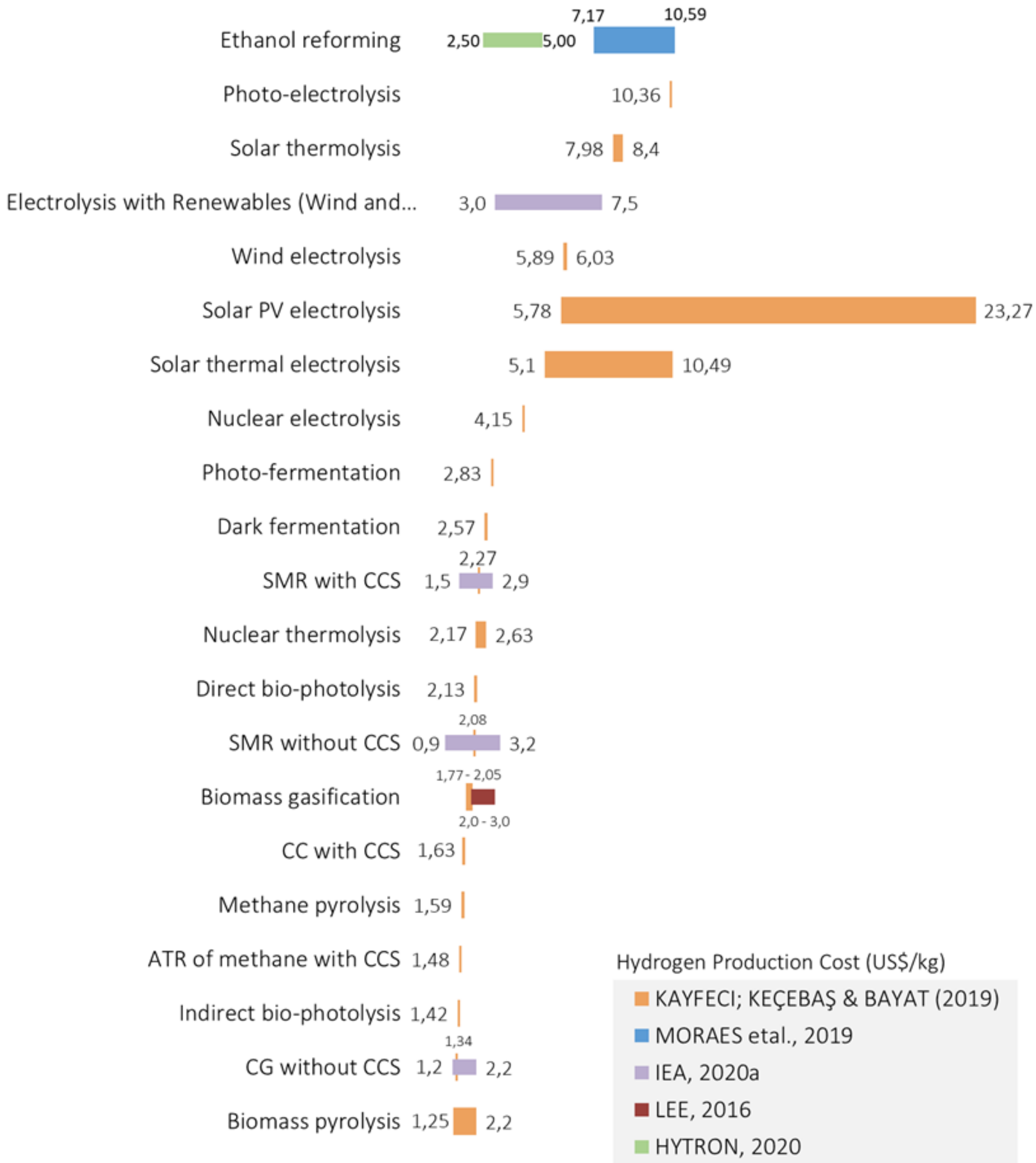


Figure 6 – Hydrogen production cost ranges

Source: KAYFECI; KEÇEBAŞ & BAYAT (2019); IEA (2020a); LEE (2016)

It is possible to follow the progress of hydrogen prices in some markets. Recently, S&P Global Platts started monitoring hydrogen price by technology and certain regions of the world (S&P GLOBAL PLATTS, 2020a). Figure 7 illustrates the hydrogen price curve during the first quarter of 2020 in California for the PEM Electrolysis and Methane Steam Reform technologies without CCUS.

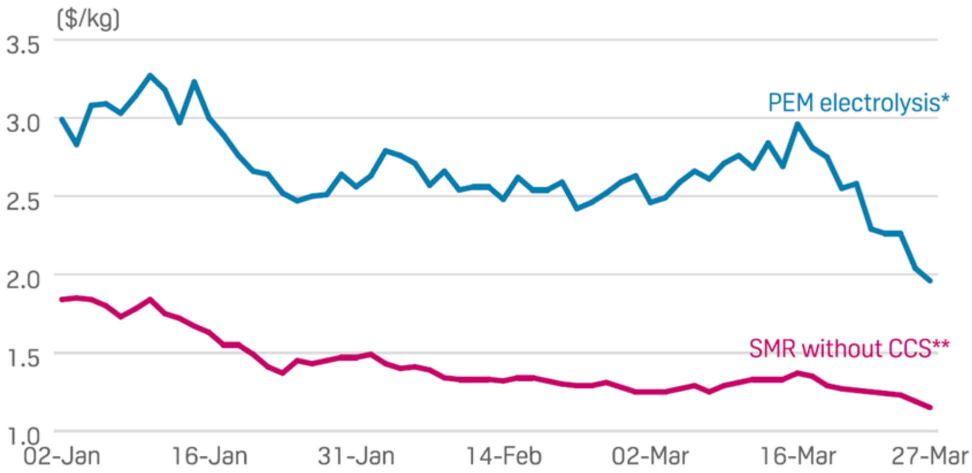


Figure 7 – Hydrogen price assessment in California Market, US, by technological route on 2020 first quarter

Source: S&P GLOBAL PLATTS (2020b)

There was a narrowing between hydrogen prices produced by electrolysis and by steam methane reforming after mid-March 2020. However, it is not possible to assure whether it is a cyclical effect related to pandemic impact, or if it is the initial long-lasting results from electrolysis costs reduction.

Nevertheless, there are studies that indicate significant cost reductions by 2030. Bloomberg New Energy Finance (BNEF, 2020), for example, forecasts cost reductions for renewable-based hydrogen and estimates that this technology should become competitive until 2030, overcoming fossil-based hydrogen until 2050 (Figure 8).

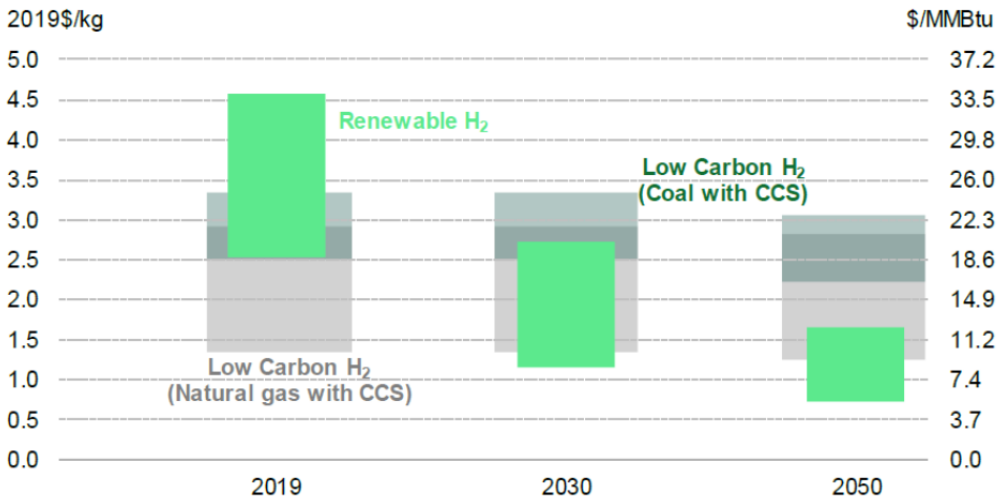


Figure 8 – Forecast range of levelized cost of hydrogen production from large projects.
Source: BNEF (2020)

According to the BNEF (2020), renewable-based electrolysis forecasts considered large projects and significant low capital expenditure (CAPEX) values. The natural gas price used ranged from USD_{2019} 1.1 to 10.3 / MMBTU for the steam methane reforming route, and for coal gasification, the price range adopted was USD_{2019} 30 to 116 / t (BNEF, 2020).

Another study found almost 60% of potential reduction on costs for green hydrogen production by 2030. The cost components CAPEX and Electricity represents the greatest opportunities for reduction (HYDROGEN COUNCIL, 2020). Figure 9 illustrates these results.

USD/kg hydrogen

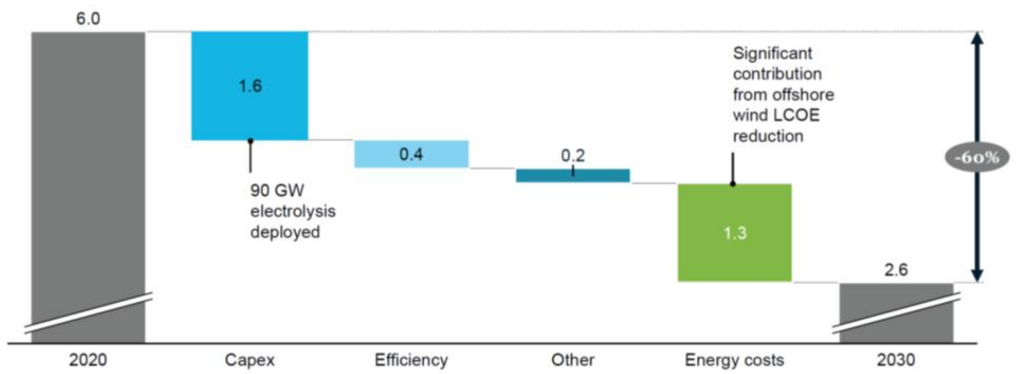


Figure 9 – Forecast cost reduction for hydrogen production from electrolysis
Fonte: HYDROGEN COUNCIL (2020)

IRENA (2019) also points out that hydrogen produced from renewable sources may become competitive, in relation to hydrogen of fossil origin, before 2025, for the best cases. Regarding world average values, competitiveness would be achieved between 2030 and 2040. The cost projection curves are shown in Figure 10.

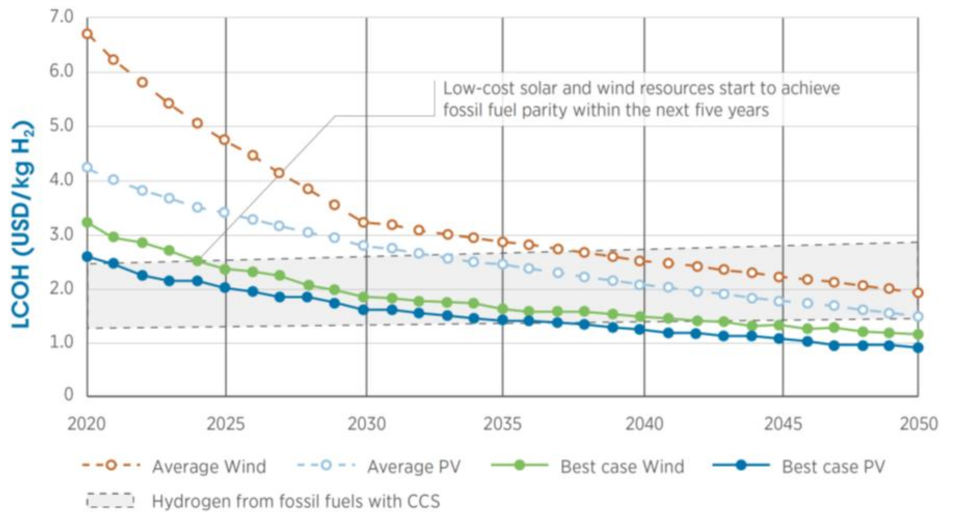


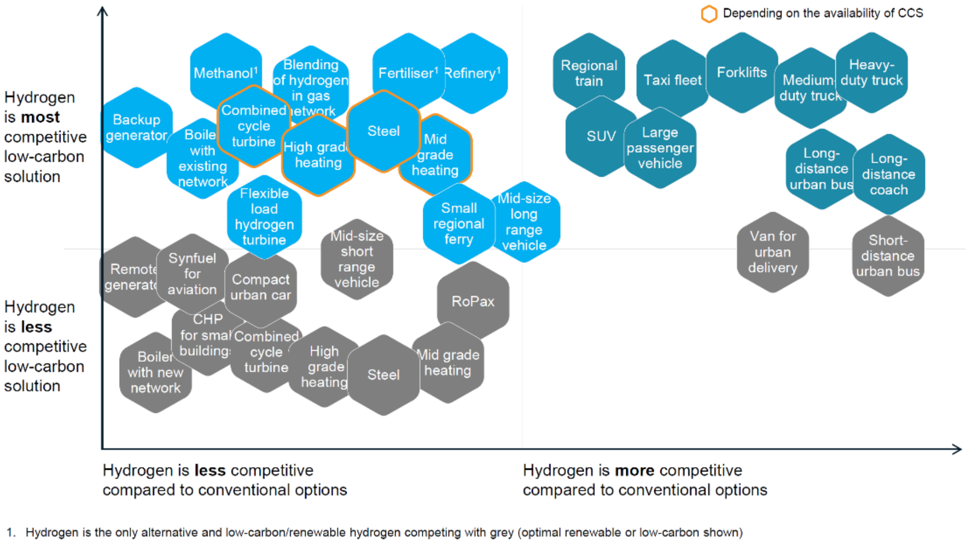
Figure 10 – Hydrogen production costs projections

Source: IRENA (2019)

HYDROGEN COUNCIL (2020) identified the same reduction results on the cost trajectory for renewable hydrogen. The report considers the Total Cost of Ownership (TCO) and assesses the competitiveness of hydrogen in 35 applications until 2030. The use of hydrogen in 22 applications may become competitive, under favorable conditions. These conditions are specific to the application and region, and include a carbon price, the availability of other renewable sources and carbon capture and storage. The report also points out that to accelerate the penetration of hydrogen in markets, governments need to support the development of national strategies, coordinate market stakeholders to capture opportunities, regulations to remove barriers, standardization, investment in infrastructure and incentives.

In addition, applications such as use in turbines, industry feedstock, and synthetic aviation fuel are expected to require a carbon price of at least USD 100/t CO2-eq. to become feasible. Table 2 shows all 35 applications considered, grouped by competitiveness versus low-carbon and conventional alternatives.

Table 2 – Competitiviness of hydrogen applications until 2030



Source: HYDROGEN COUNCIL (2020)

Later, HYDROGEN COUNCIL (2021) reaffirmed the trajectories identified in its 2020 report, pointing to an acceleration of the downward trend in hydrogen production costs from renewable sources (60% reduction from 2020 to 2030). According to the document, when introducing carbon costs (USD 50/tCO2 eq. in 2030, USD 150/tCO2 eq. in 2040 and USD 300/tCO2 eq. in 2050), the price of indifference (breakeven) between green hydrogen and gray may occur between 2028 and 2034.

Subsequently, HYDROGEN COUNCIL (2021) reaffirmed the trajectories identified in its 2020 report, pointing to an acceleration of the downward trend in hydrogen production costs from renewable sources (60% reduction from 2020 to 2030). According to the document, when introducing carbon costs (USD 50/tCO_2 eq. in 2030, USD 150/tCO_2 eq. in 2040 and USD 300/tCO_2 eq. in 2050), the breakeven price between green and gray hydrogen may occur between 2028 and 2034.

5 Challenges for market development of hydrogen energy use

The production and industrial uses of hydrogen in Brazil are relatively consolidated. However, the broader use of hydrogen-based energy projects will require a more continued investment in research, development, and innovation to allow the country to become a relevant actor in the Hydrogen Economy. The diffusion of new technologies, the development of an infrastructure of production, storage, transport, and distribution of hydrogen are important topics to be addressed in this context. Advances in the standardization and certification of industries, and partnerships with countries with more developed technologies are also part of this agenda (CÉSAR et al., 2019).

In addition to the standardization of safety conditions and the design and regulation of the market, the main challenge for the development of the energy use of hydrogen is to achieve competitiveness levels with other sources through costs reduction, according to the projections of the studies mentioned above.

In the technological aspect, along all routes there are numerous challenges to overcome, although hydrogen production and use is already a reality in specific niches, as in the case of forklifts. But hydrogen storage is a challenge apart. Being the lightest chemical, increasing its energy density by volume requires high pressures for storage in the gaseous state, or cryogenics for storage in the liquid state. Adsorption storage technologies currently also require low temperatures and high pressures. Additionally, hydrogen is an explosive gas, which affects risk perception.

In relation to logistics, the decision between centralized or distributed hydrogen production can circumvent the absence of a transport and distribution network. Electrolysers or reformers can be installed near the place of supply or consumption. However, the business model must be decided by the market.

It is essential to understand the hydrogen diffusion model in the energy matrix: 1) to reveal the market development sequence, which will catalyze its industry; 2) to avoid technological lock-ins in the future, as its competitiveness increases (see Figure 11); and, 3) to identify the current market profile of hydrogen, by segment.

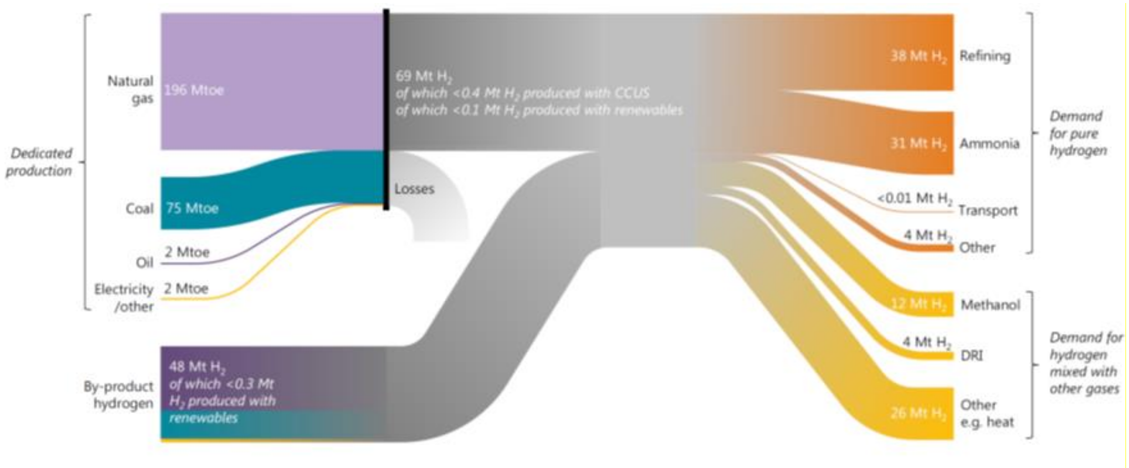


Figure 11 – Hydrogen value chain
Source: IEA (2019a)

The possible competition between fuel cells and batteries (and even ultracapacitors), especially in the transport sector, raises some questions. For example, will there be leap frogging in fuel cell vehicles and, consequently, overcoming electric battery vehicles (forging ahead & falling behind)? Or will the technological standard of light vehicles be battery electromobility?

The same applies to energy storage for the electricity sector. In addition to the existing hydropower (reservoir or reversible) plants in the world, what other technology will provide energy storage? Hydrogen? Batteries? Or a combination of these technologies?

An institutional, legal, and regulatory framework appropriate to the energy use of hydrogen, still non-existent, will also be necessary to provide security to industry and consumers. What will be the institutional and the legal governance? Who will regulate and monitor the market? What regulations will be required to ensure safety conditions, process certification, human resources, and fuel specification? Will there be technological lockdown on specific hydrogen generation routes? All these issues will need to be addressed in the coming years, not only in Brazil, but around the world.

6 Hydrogen role in energy transition

As previously mentioned, hydrogen market has gained momentum from post-pandemic energy policies to help economy recovery and to accelerate energy transition in several countries (IEA, 2020b).

In addition to being able to be used directly in hard to electrify sectors, as a low or zero carbon energy source (depending on the process), hydrogen can also be used as a vector for energy storage, enabling greater input of variable renewables such as wind, solar etc. For its versatility of use and ability to store energy, hydrogen is considered a resource able to promote coupling between the markets of fuels, electricity, industrial, among others. In this sense, hydrogen can not only contribute to the deep decarbonization of the world economy, but also promote greater competitive, broad, and decentralized dynamics by coupling the different market segments.

For no other reason, as of 2018, several national governments have announced or strengthened hydrogen strategies and policies (IEA, 2019b). It is noteworthy that the strategies emphasize as a central challenge for green hydrogen the need to reduce costs.

The USA early in 2002 released their prospects in “A National Vision of America's Transition to a Hydrogen Economy — to 2030 and Beyond” and its roadmap “The National Hydrogen Energy Roadmap” and, subsequently, its plans “Hydrogen Posture Plan”, in 2006, and “The Department of Energy Hydrogen and Fuel Cells Program Plan”, in 2011. Later, the USA updated and expanded its strategy in 2020, launching the document “The Department of Energy Hydrogen Program Plan”, which sets goals for hydrogen and its related technologies to become competitive in the market against its competitors from the technical advances needed to do so beyond the 2050 horizon.

Japan organized the first Ministerial Meeting on Energy Hydrogen, which resulted in the Tokyo Declaration defining four main areas to accelerate the progress of hydrogen technology. In March 2019, Japan changed its Technology Map for Fuel Cells and Hydrogen, setting more quantitative cost targets. Australia, in August 2018, published a Hydrogen Technology Map and announced plans to launch its Hydrogen Strategy in December 2019.

South Korea announced its Hydrogen Technology Map in January 2019, targeting the production capacity of 6.3 million fuel cell electric vehicles and 1,200 refueling stations by 2040.

France announced the Hydrogen Development Plan for energy transition in June 2018. The French plan includes targets of 20% to 40% use of low carbon hydrogen in industrial applications, and a reduction in the cost of electrolysis to reach the range of 2 to 3 €/kg H_2 by 2028.

Germany, which consolidated its National Hydrogen Strategy in June 2020, has strengthened funding of more than €1 billion to be applied in hydrogen under Germany's Decarbonisation Programme between 2020 and 2023, with an additional €7 billion to accelerate the development of the German market and €2 billion to support international partnerships, recognizing that the country will need large-volume imports to meet the established carbon emission reduction targets (GERMANY, 2020).

In August 2020 Portugal approved its National Hydrogen Plan, which displays green hydrogen as a relevant vector for the energy transition in the country (PORTUGAL, 2020). Among the objectives until 2030, mentioned in the document, are: 1) injection of 10 to 15% of green hydrogen into the natural gas network; 2) Construction of 50 to 100 hydrogen filling stations; and 3) construction of 2 to 2.5 GW of installed capacity of electrolysers.

6.1 The Opportunities of Brazilian hydrogen for energy transition

Brazil has also shown interest in the development of hydrogen. In 2002, the Ministry of Science and Technology (MCT) launched the Brazilian Hydrogen and Fuel Cell Systems Program (initially called PROCAC). Later, in 2005, this program was renamed to "Science, Technology and Innovation Program for the Hydrogen Economy", with the acronym PROH2 (LINARDI, 2008).

Also, in 2005 the Ministry of Mines and Energy (MME) coordinated the so-called "Roadmap for the Structuring of the Hydrogen Economy in Brazil". This was a broad study conducted together with the Ministry of Science and Technology – MCT, dozens of specialists from Brazil and abroad, national, and foreign companies, institutes and research centers, regulatory agencies and metrology institutes (MME, 2005). The topics addressed in this study were:

- Bases for Hydrogen Market Development.
- Hydrogen Production.
- Hydrogen Logistics.
- Conversion Systems.
- Hydrogen Applications as an Energy Vector.
- Technological Development and Human Resources Training.
- Metrology, Standardization, Technical Regulation, Conformity Assessment, Regulation and Supervision.

In each of these topics, a contextualization and description of the current situation was made, describing prospects and barriers to its implementation, evaluation of technological maturity and actions to be implemented.

The "Roadmap for the Structuring of the Hydrogen Economy in Brazil" (MME, 2005) already provided some relevant guidelines to the national strategy, including:

- The valorization of different technological routes in which Brazil could have competitive advantages, such as: ethanol (not only by reform, but also by direct oxidation in fuel cells), electrolysis of water (using secondary electricity of hydroelectric plants), and other biomass, in addition to sugarcane, including biogas.
- Recognition of the role of natural gas to facilitate the transition to a phase dominated by green hydrogen.
- The definition of a market diffusion logic for hydrogen: distributed energy generation, energy production in isolated regions and urban buses.

The document also established a 20-year schedule for achieving goals, related to each proposed theme, and provided for the launch of a Government Program for the Production and Use of Hydrogen in Brazil after 2007. Subsequently, the launch of a Government Program was planned for 2010 ahead, as shown in Figure 12 (MME, 2009).

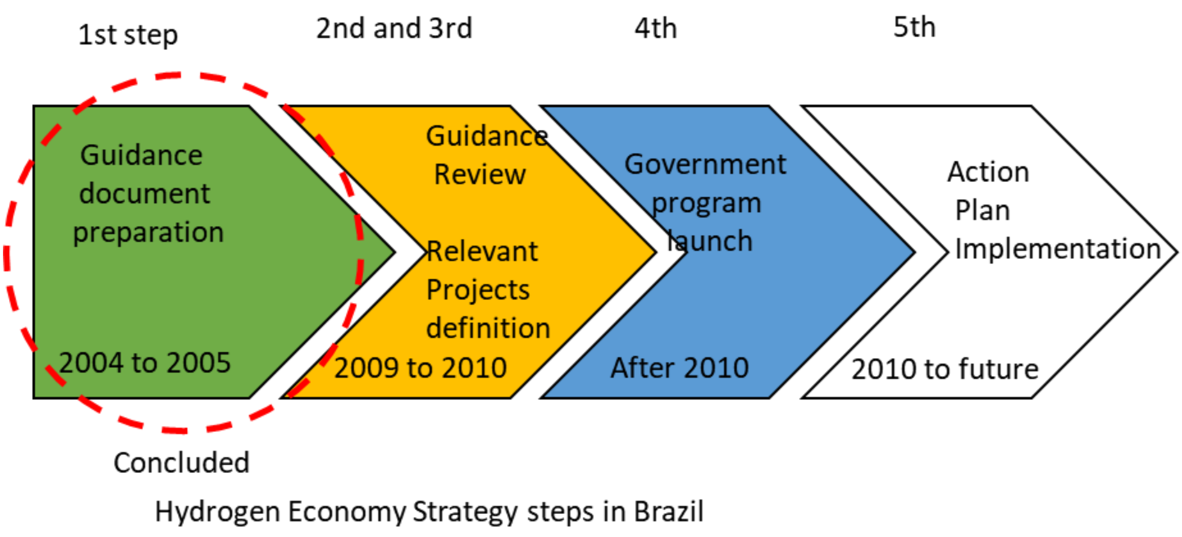


Figure 12 - Steps towards structuring the Hydrogen Economy in Brazil
Note: Roadmap for structuring the Hydrogen Economy in Brazil - March 2005 (revised)
Fonte: MME (2009)

Figure 13 presents the main priorities of the "Roadmap for the Structuring of the Hydrogen Economy in Brazil", with the prediction of the commercial use of hydrogen.

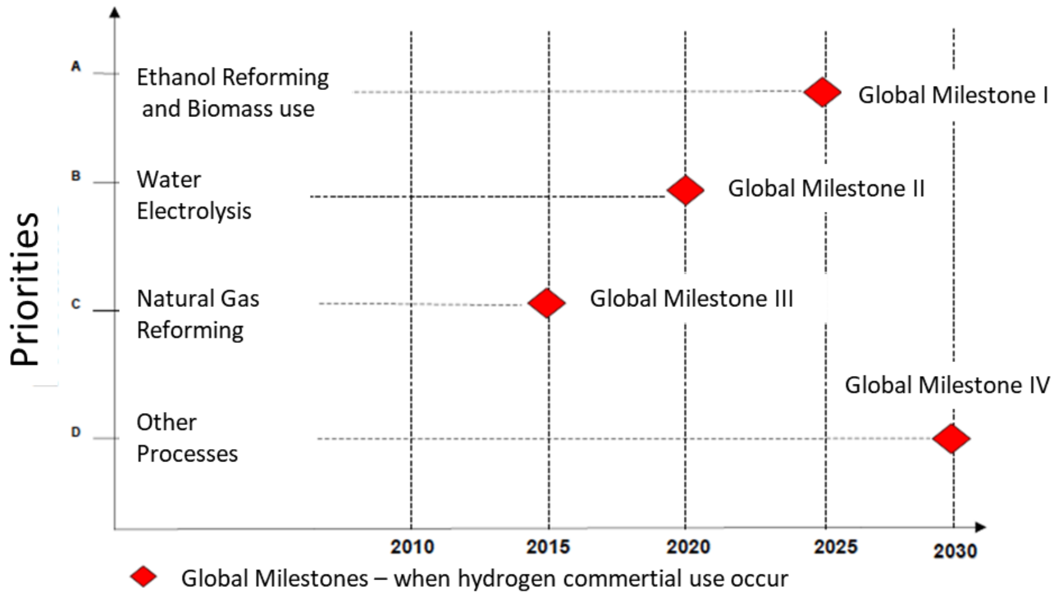


Figure 13 - Priorities of the Roadmap for the Structuring of the Hydrogen Economy in Brazil

Source: MME (2009)

With the pre-salt discoveries in 2006, there was a change of priorities in the energy policy agenda and the Government Program for the Production and Use of Hydrogen in Brazil was not launched, although several projects associated with hydrogen continued to be developed.

In any case, it is important to point out that several technological projects, associating universities, research institutes and companies, have been able to develop applications for hydrogen generation. Examples of these projects are: 1) CEMIG-Clamper, the Polytechnic School of USP (University of São Paulo), with FIPAI-EESC-USP (Foundation for the Increase of Research and Industrial Improvement), EESC-USP (School of Engineering of São Carlos) and IQSC-USP (Institute of Chemistry of São Carlos), both of USP campus of São Carlos, and UNITECH; 2) Itaipu Binacional-PTI (Itaipu Technological Park) in partnership with UFPR (Federal University of Paraná) and TECPAR (Instituto de Tecnologia do Paraná), through CERBIO (Brazilian Center for Reference in Biofuels); 3) The IPEN (Institute of Energy and Nuclear Research), which incubated Eletrocell and maintains collaborations with CEPEL (Center for Electric Energy Research) of Eletrobras, CENPES (Leopoldo Américo M. de Mello Research and Development Center) of Petrobras, INT (National Institute of Technology), IPT (Institute of Technological Research), UNICAMP (University of Campinas), IQSC-USP, and UNESP (State University of São Paulo) Bauru campus; 4) COPPE/UFRJ, which structured the Hydrogen Laboratory and the Reference Center in Hydrogen Technology and Economy, with national scope, in partnership with CEPEL/Eletrobras (VARGAS et al., 2006).

It should also be noted that, as a result of investments in Hydrogen Research and Development in Brazilian universities, over the last decades, innovative companies, incubated in research centers or founded by researchers, have acted prominently on the national scene and abroad. These include Hytron, Ergostech, BASE-Sustainable Energy, Electrocell and Novocell (VALOR ECONÔMICO, 2019; MACEDO & VELA, 2020). In addition, the country has several companies in the automotive chain, in the gas and energy industry that already develop solutions and products related to hydrogen.

It is also worth mentioning the relevance of investments in Research, Development and Demonstration (R&D) in the energy sector, including hydrogen, which began to be consolidated and mapped from the Energy Big Push project, a partnership between EPE, MME, CGEE, ECLAC and several national and international partners, especially the International Energy Agency (IEA). One of the axes of the project was dedicated to the construction of a database of public and publicly oriented R&D investments (regulated by ANEEL and ANP) in the period from 2013 to 2018, following the technological classification already adopted by the IEA. The results available in the newly released project reports (ECLAC & CGEE, 2020) show that hydrogen still has a very timid share of investments in R&D. In 2018, only 0.9% of public investments and 0.2% of publicly oriented investments were allocated for hydrogen.

The Energy Big Push database also exhibits the profile of hydrogen projects for some institutions (ANEEL, ANP and FNDCT). From 2013 to 2018, 91 hydrogen and fuel cells related projects received investments around R$ 34 million. By analyzing the results, we perceive a characteristic of similar projects in the ANEEL and ANP programs, both in terms of project duration (~44 months) and amount granted (ranging from R$ 1.5 million to R$ 1.9 million). On the other hand, the financing related to FNDCT is shorter term (~26 months), more numerous (74 projects), smaller financial (average of R$ 76,000) and more linked to basic research. Figure 14 shows the maximum, average, and median disbursements for these projects, by source of resources.

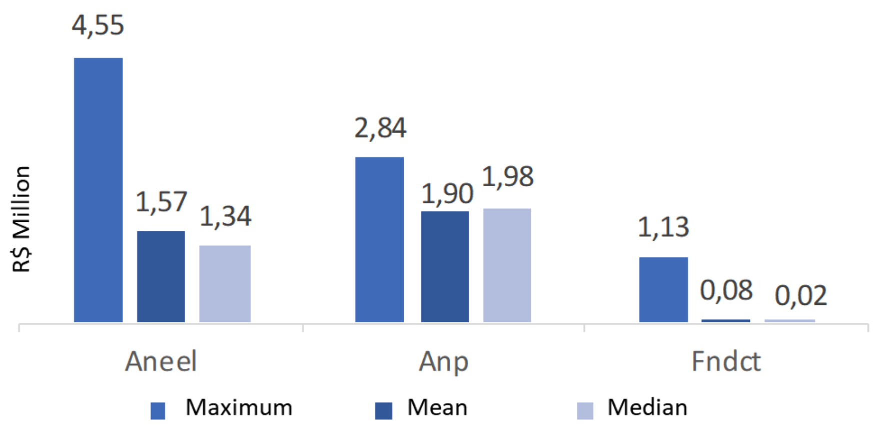


Figure 14 – Disbursements for hydrogen projects of the R&D programs of ANEEL, ANP and FNDCT.

Source: Energy Big Push Brazil database (ECLAC & CGEE, 2020).

In 2010, the Center for Management and Strategic Studies (CGEE), under commissioning of MCTI, launched the document "Energy hydrogen in Brazil: Subsidies for competitiveness policies: 2010-2025", from the “Critical and Sensitive Technologies in Priority Sectors" series. In this document, there are international and national scenarios, considerations and discussions of bottlenecks and proposals on four themes: 1) Hydrogen Economy; 2) Hydrogen Production; 3) Development of Hydrogen Logistics; and 4) Hydrogen Use Systems (CGEE, 2010). The document presents a detailed diagnosis about bottlenecks, consisting of a very important starting point for the consolidation of an institutional, legal, and regulatory framework that needs to be established for the blooming of a hydrogen economy.

Both MME's "Roadmap for structuring the Hydrogen Economy in Brazil", published in 2005, and the document "Energy Hydrogen in Brazil: Subsidies for competitiveness policies: 2010-2025", from CGEE, published in 2010, bring elements necessary to build the national hydrogen strategy. They point out a strategy that takes advantage of Brazil's competitive advantages (ethanol, hydroelectricity, wind, solar, natural gas, nuclear, biogas and other biomass) to develop new competitive advantages in the energy transition focused on the role of hydrogen. A strategy in which all colors matter, a "rainbow" hydrogen strategy.

It should also be emphasized that ABNT (Brazilian National Standards Organization) has been discussing the standardization of hydrogen technologies in the country, from production to final use, within the working group of the Special Study Commission on Hydrogen Technologies - ABNT/CeE-067 (ABNT, 2021).

In addition to the governmental actions mentioned above, initiatives of international partnerships and projects can also be highlighted, aiming to accelerate the formalization of the national hydrogen strategy:

- Participation in the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE). MME was Brazilian first representative and, currently, it is exercised by the Ministry of Science, Technology and Innovation (MCTI);
- After German Hydrogen Strategy disclosure in 2020, partnerships between MME and Germany have begun to incorporate activities aimed at identifying possibilities for hydrogen cooperation, especially regarding the supply of green hydrogen to meet Germany's future demand, such as:
  - Under the Brazil-Germany Energy Partnership, the Green Hydrogen Sector Mapping Study in Brazil aims to identify the main agents of the hydrogen value chain and offer an overview of the main technologies for green hydrogen production and "*Power-to-X*" under development in the country.
  - As part of the Energy Storage Technologies Cooperation Project, a study is being developed to survey the potential for green hydrogen production in Brazil, in order to support the development of a new roadmap for the hydrogen economy in Brazil.
- Composition of the Brazil-Chile working group to conduct a technical-exploratory study on the potential of bilateral cooperation in hydrogen. The interest of that country in the local production of the so-called "green hydrogen", with intentions of investment in this field, of the order of US$ 200 billion in the next 20 years, stands out.

Other international cooperation initiatives are underway, either bilaterally or multilaterally, such as the *Hydrogen Initiative* (H2I) which is part of the Clean Energy *Ministerial* (CEM). Arrangement of several countries focused on the promotion of clean energies, in which Brazil participates.

Finally, in February 2021 the National Energy Policy Council (CNPE) pointed to hydrogen as one of the priority themes for research and development in the country, aiming at the application of publicly oriented resources.

Such *momentum* has generated a very favorable business environment, engaging several agents for the development of the hydrogen market. In particular, given the significant competitiveness of variable renewables (wind and solar) in Brazil, there has been special interest, by foreign partners (especially Germany) and national and international entrepreneurs, in developing green hydrogen in the country. Much of the focus is on the development of projects for hydrogen export, directly or indirectly, in the form of ammonia and methanol.

In this context, we highlight the recent partnership of the Government of Ceará with the Federation of Industries of the State of Ceará (FIEC), the Federal University of Ceará (UFC) and the Pecém Complex (CIPP S/A). To this end, a Decree was signed on

February 19th 2021, to set up the Working Group to develop public renewable energy policies for sustainable development and for the configuration of the green hydrogen HUB in the State of Ceará (GOVERNMENT OF THE STATE OF CEARÁ, 2020).

6.2 Hydrogen in the National Energy Plan 2050

The National Energy Plan 2050 (PNE 2050), approved in December 2020 by the Ministry of Mines and Energy, has hydrogen as part of the Brazilian energy strategy.

In fact, hydrogen is pointed out in PNE 2050 as a disruptive technology and is mentioned as an element of interest in the context of the decarbonization of the energy matrix, the insertion of distributed energy resources, the search for expansion of the forms of energy storage and management of power supply flexibility, the prospects of application of nuclear energy and natural gas.

In the case of the insertion of electric vehicles in the transport sector, PNE 2050 points to the technological perspective of the use of fuel cells, with hydrogen produced from liquid biofuels, natural gas or biomethane.

Another point considered in PNE 2050 is the prospect of hydrogen mixing in natural gas networks, in percentages and with limited pressures, for transport and storage purposes, as a way to better use this infrastructure and to provide important volumes of hydrogen for energy purposes.

In the context of the process of decarbonization and hydrogen insertion, PNE 2050 highlights as a recommendation for energy policy:

- To stimulate the possibilities that the use of hydrogen allows for the decarbonization of sectors such as: industry (petroleum refining, petrochemical, chemical, steel, etc.) and transport, among others.
- To design regulatory improvements related to quality, safety, transportation infrastructure, storage, and supply, as well as to encourage and to promote the use of new technologies.
- To articulate initiatives with international institutions in hydrogen.

This document is an effort to deepen and update the role of hydrogen in the Brazilian energy policy and in determining the actions required in this context, incorporating recent events and developments in the international scenario.

7 Final remarks

This Technical Note aimed to provide an overview of hydrogen industry, its challenges, and opportunities, considering the most recent papers about technology development, costs, and national strategies, as well as historical data from Brazilian initiatives regarding hydrogen development.

Brazil has been investing in research and development of hydrogen production and use technologies. Moreover, the Brazilian government already has important studies to support the Brazilian national strategy for hydrogen development.

The country has a variety of research and development activities related to hydrogen. There are several research groups in many universities and other institutions. In addition, there are also companies that already work in the hydrogen market, and a national association that brings together companies and other stakeholders (the Brazilian Hydrogen Association - ABH2), which can contribute to the stakeholder engagement in building the institutional, legal, and regulatory framework, and public policies to promote a hydrogen economy.

More than establishing the Brazilian hydrogen strategy, which has existed in practice since 2002-2005, it is important to consolidate and formalize the national strategy in specific federal government´s action plan. This will require updating the guidelines and overcoming the challenges already identified in the documents prepared by MME and MCTI. Finally, as previously mentioned, for the Brazilian hydrogen strategy all colors matters, in a “rainbow” hydrogen strategy, which allows the country to make the most of its existing competitive advantages and build new competitive advantages for the benefit of its society.

In practice, this means that Brazil must embrace the opportunities for the development of various technologies for the production and use of hydrogen, including "green" hydrogen, in which it can be very competitive, but not limited to it. This approach is shown to be the most consistent and promising to enable a trajectory of deep decarbonization of energy systems, accelerating the formation of markets, avoiding technological lock-ins, and taking advantage of the diversity of energy resources in the country.

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