

Review

Occurrences and Perspectives of Natural Hydrogen Extraction: The Brazilian Context

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Abstract: The global energy matrix needs to undergo considerable changes to achieve the clean and affordable energy target as per the Sustainable Development Goals determined by the United Nations (UN) by 2030. Hydrogen has stood out worldwide as a potential substitute for current non-renewable sources. Once thought to be minor, if not non-existent, natural hydrogen is now becoming a more significant alternative that is being explored. Natural hydrogen can be obtained from subsurface rocks by the generation process of serpentinization, radiolysis, rock fracturing, or magma degassing, using extraction technology similar to that already used in the oil and gas industries. Thus, the goal of this research was to perform a consistent technical–scientific and bibliometric review of natural hydrogen, presenting the Brazilian context. The results showed that from 2017 onwards, there has been an increase in research publications related to the topic. France is the country with the most publications. In Brazil, the potential of natural hydrogen sources has been studied in states such as Goiás, Tocantins, Minas Gerais, Roraima, Bahia, and Ceará. It is still difficult to predict the potential cost of natural hydrogen production. However, estimates through the Hydroma company show a cost of 0.5 USD/kg, and Australia and Spain target price projects at approximately 1 USD/kg of natural decarbonization could be aided by natural hydrogen, which could supply the world’s energy needs for generations. Geological processes, reserve behavior, and the efficiency of extraction are among the unknowns, though. Brazil requires a strong regulatory framework and additional research. For exploration to be sustainable, cooperation between the government, businesses, and society is essential.

Keywords: drilling; extraction; geological hydrogen; natural hydrogen; database



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1. Introduction

Considering the rapid development of the world’s economies and societies, as well as the rise in energy consumption, conventional fossil energy sources such as oil, natural gas, and coal have been greatly reduced. In the same context, it is fair to mention that the greenhouse effect has intensified and, as a consequence, environmental pollution has also increased over the past years [1]. In Brazil, for instance, oil production was 3.470 million barrels per day (bbl/d) in October of 2024, where 78.41% was extracted from Pre-salt reservoirs [2]. In a global perspective, energy grew 1.1%, an increase of 410 million tons

(Mt), reaching a new record of 37.4 billion tons (Gt). Emissions generated from hydrocarbon-related combustion, in a global perspective, have reached amounts in the order of 100 Mt CO₂, with the considerable participation of China, despite the reduction in several regions, like Brazil. It is valid to highlight that carbon emission intensity related to petroleum and gas exploration in Brazil is lower than the global average [3].

In 2015, during the United Nations Climate Change Conference, the Paris Agreement was signed, aiming to restrict worldwide average temperature rises to 2 °C per year [4,5]. Meanwhile, Brazil proposed the National Energy Plan (PNE 2050) that deals with the current energy transition process, consisting of a process of transformations towards an economy that prioritizes the reduction of carbon emissions. In this context, there are incentives to prioritize the use of energy resources more efficiently and to decrease the use of carbon-intensive fuels in the global primary energy matrix in favor of low-carbon sources, especially renewables, as well as the electrification of energy conversion processes [6]. This means replacing fossil fuel-using devices or procedures, such as gas boilers and internal combustion engines, with electrically powered alternatives, such as heat pumps or electric cars [7].

Hydrogen is emerging as a powerful and significant energy route as the world moves toward a more sustainable and low-carbon society [8,9]. Hydrogen, at different times known as the “fuel of the future” or “the most ideal new energy of the 21st century” [1,10,11], is considered a promising alternative to the present scenario due to its high versatility, cleanness, and energy-related capability [8,12].

For decades, natural hydrogen was overlooked, as it was presumed that it either occurred in small amounts or faded away too quickly. Additionally, the techniques employed in field studies were frequently ill-fitted to their specifications, unable to effectively detect their presence [8,13]. However, for millions of years, natural hydrogen has been seen, like in the perpetual flames atop Mount Chimaera in Turkey; in more recent times (one hundred years ago), a borehole in Australia yielded hydrogen but was closed off as an inconvenience [14].

As a potential new carbon-free energy source, natural hydrogen is not yet a major player in the current discussion surrounding hydrogen and its role in the energy transition process. Its existence, as well as its potential, is still unknown to the general public. However, some energy experts think it is an intriguing substitute for the costly and energy-inefficient process of producing hydrogen from fossils or renewable resources [14].

As petroleum is preserved throughout time, natural hydrogen is also produced through geological processes, and it can be trapped through impermeable barriers on its way to the atmosphere [8]. Natural or geological hydrogen can be found at shallow depths under suitable geological circumstances [15]. One potential economical and sustainable way to produce hydrogen is by extracting naturally occurring hydrogen, which could aid in the decarbonization of the energy matrix [14,15].

The search for natural or geological hydrogen requires skills resembling those applied in the petroleum industry, especially related to exploration and drilling [8,16]. For instance, seismic prospecting can be used to initially localize natural hydrogen deposits [17], while chromatographic analysis would offer more information about its composition and confirmation of the type of gas that was reached [18], requiring drilling in the loop of the processes.

The commercial exploitation of hydrogen is a feasible option and can be very promising for accessing low-carbon products. In the new legal framework for hydrogen in Brazil, the National Agency of Petroleum (ANP) will be responsible for regulating the sector using specific grant modalities pointed out in an intralegal decree in the exploration and production of the substance [15].

In this route, natural hydrogen can be a promising potential to aid in the decarbonization of several industries [8]. Nowadays, industry uses hydrogen extensively in processes including metallurgy, steel, refineries, and fertilizer manufacture. In Brazil, there are numerous industries with a high potential for replacing main inputs with low-carbon hydrogen, including cement, glass, mining, steel, and gasoline [19].

Despite the clear importance of natural hydrogen, the current understanding of natural hydrogen occurrences is limited due to the lack of fundamental understanding of the reaction mechanisms and rates associated with geochemical processes of formation, migration, and accumulation within the subsurface [16]. However, a number of nations have changed (or are changing) their mining laws to provide industrial projects the legal structure they require. Countries like Australia, Mali, Morocco, Congo, Ukraine, France, and Germany have all perceived this tendency [15]. In this perspective, this research proposes a technical-scientific overall study and a bibliometric review about natural hydrogen.

2. Contextualization

The energy sector is crucial for a nation to grow, develop, expand, and achieve security guarantees [20,21]. The world energy matrix in terms of demand, as shown in Figure 1, is mostly constituted of non-renewable sources, totaling 80% of oil and derivatives, natural gas, and coal minerals.

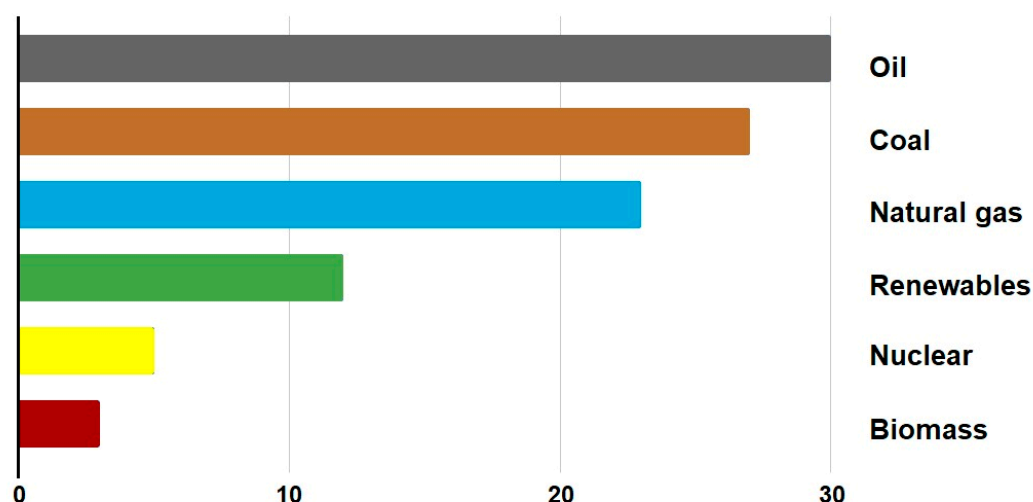


Figure 1. Global energy matrix—2023. Renewables include solar, hydro, wind, and bioenergy. Source: Adapted from [22–24].

The eventual limited access to existent fossil fuel reserves (at least over a moderated perspective), as well as the actual heterogeneous distribution of proved reserves over the world, attached also to the non-environmentally friendly characteristics it may have, can be seen as potential factors driving the actual society to a scenario where the dependence on this source of energy has been set to be limited [5]. To meet the CO₂ net-zero targets, numerous technologies are expected to help lower emissions without compromising the energy security of future generations, in which case fossil fuels may become lose competitive [25]. It is still important to understand and emphasize that to precise the exact timing and extent of energy transitions is intrinsically challenging due to the complexity of many factors to forgo through changes, such as market structures, resource availability, sociopolitical dynamics, global unexpected events, volatile consumer demands guided by lifestyle, economic capabilities, among many others [26,27]. Figure 2 presents the Energy Matrix for Brazil and worldwide.

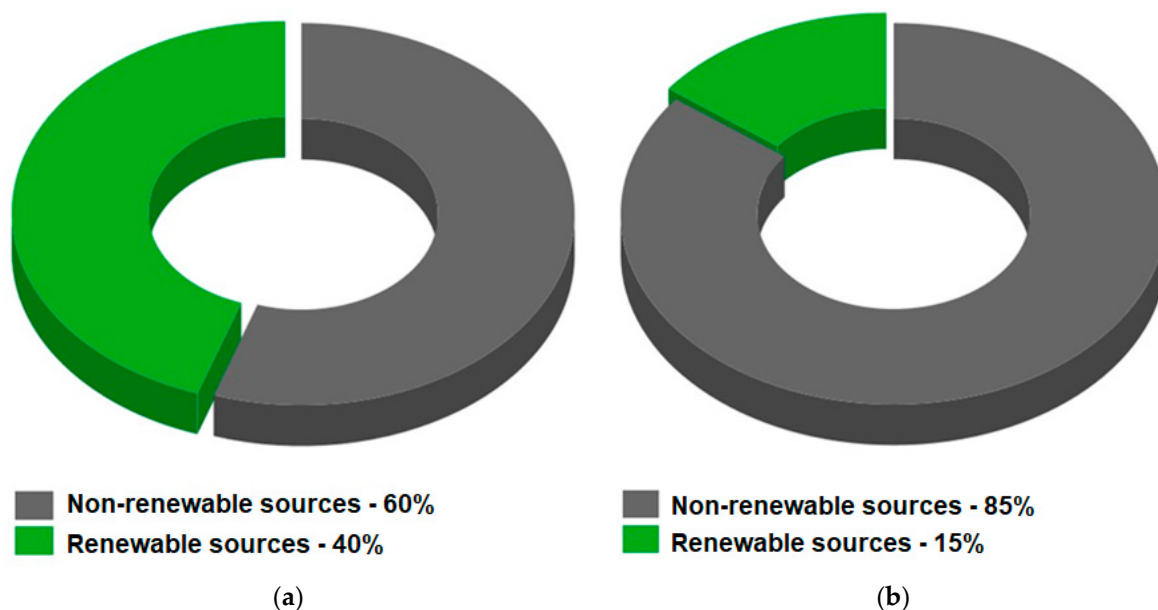


Figure 2. Energy matrix 2023 in (a) Brazil and (b) worldwide. Source: Adapted from [28].

Considering Figure 2, the Brazilian energy matrix is more renewable-driven when compared to the globe in an overall and general average. The Brazilian matrix is composed notably of renewable energy sources, such as hydropower and sugarcane derivatives [29]. This fact is important because non-renewable energy sources are directly linked to greenhouse gas emissions [30].

In this sense, concerns about environmental impacts and energy security started patronizing hydrogen, in many countries, including Brazil, due to its great applications and significance to energy and climate strategies. Hydrogen is an element abundant on Earth [31]. And has been seen by world policymakers as a vital source of energy for supporting climate change agreements [32–34]. In the years ahead, the use of hydrogen is expected to grow intensely [35]. Global hydrogen use reached approximately 95 MMt (million metric tons) in 2022 and is expected to reach more than 150 MMt in 2030 [36].

The [37] reported that in 2022, China accounted for 29% of the global hydrogen consumption, followed by 17% in North America, 13% in the Middle East, 9% in India, and 8% in Europe. The remaining regions accounted for 24% of global hydrogen consumption. Hydrogen has been used mainly in the processes of refining (41.9 MMt), for generating and producing ammonia (32.9 MMt), as well as for producing methanol (14.9 MMt), and steel (5.1 MMt) [37]. For 2030, it has been forecasted that some changes in these numbers are expected, indicating 37.0 MMt for processes of refining, 34.5 Mt for generation and production of ammonia, while 17.1 MMt and 12.7 MMt are expected for methanol and steel, respectively.

In the actual scenario and in an overall perspective, Brazil follows the global tendency of natural gas reforming, targeting the refining and fertilizer industries, which are commonly producers of large amounts of carbon dioxide [29]. However, based on announced projects, Latin America could reach almost 6.0 MMt by 2030, using electrolysis for hydrogen production, predominantly Chile (representing 45.0% of the electrolytic hydrogen production forecast for Latin America), Brazil, and Argentina (representing 30.0%) [36]. The investment estimated is about USD 25 billion for Brazil [38,39], and is located in the regions shown in Figure 3.

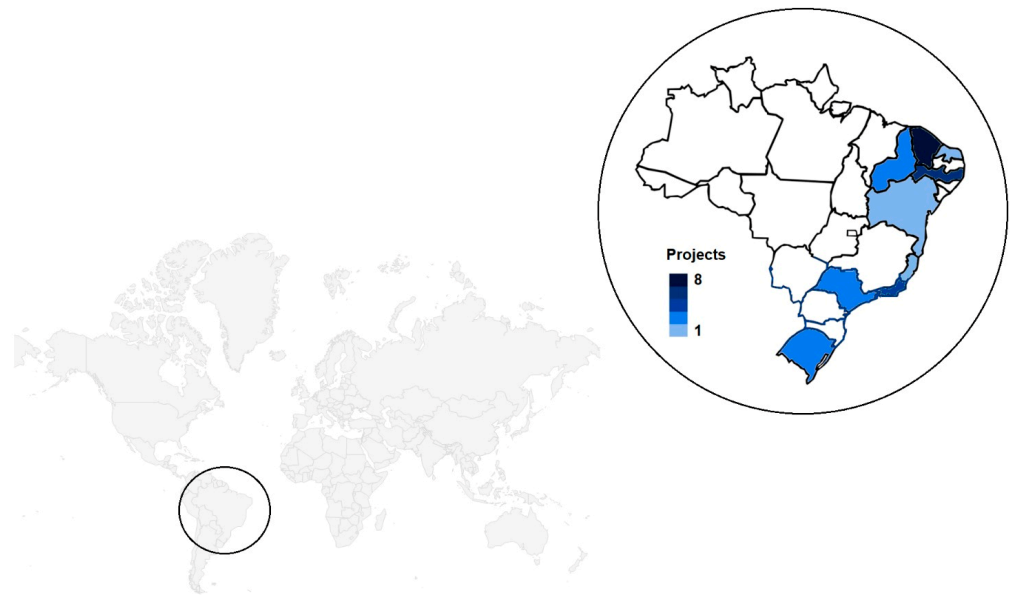


Figure 3. Brazilian initiatives associated with hydrogen production. Source: Adapted from [23,38,39].

According to Figure 3, the Brazilian investments are concentrated mostly in Ceará, Pernambuco, and Rio de Janeiro, in the Ports of Pecém, Suape, and Açu, respectively. Key elements were factored into choosing the locations of industrial port complexes, mainly focused on the development of the hydrogen chain, combining strategic factors, such as export logistics, closeness to industrial centers, and renewable energy sources [40]. The projects in Brazil are divided into concept, demonstration project, feasibility study, construction, and operation phases are expected to produce 12,921 MW and 2237 kt/year of hydrogen by 2030 [41]. The National Hydrogen Program, which defines these strategies for Brazil, is based on three timeframes: (i). establish low-carbon hydrogen pilot plants around the country by 2025; (ii). establish Brazil as a competitive low-carbon hydrogen producer by 2030; (iii). establish low-carbon hydrogen hubs in Brazil by 2035 [36]. Figure 4 presents a basic representation of the technological paths to produce hydrogen.

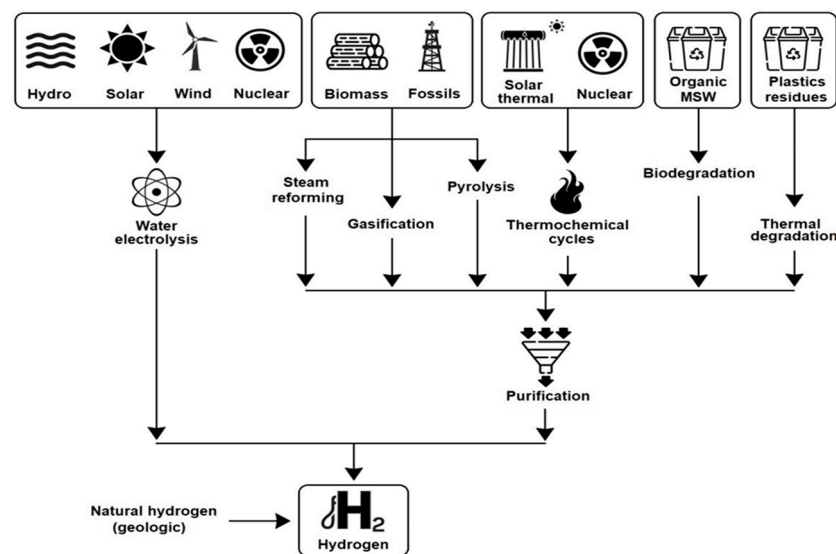
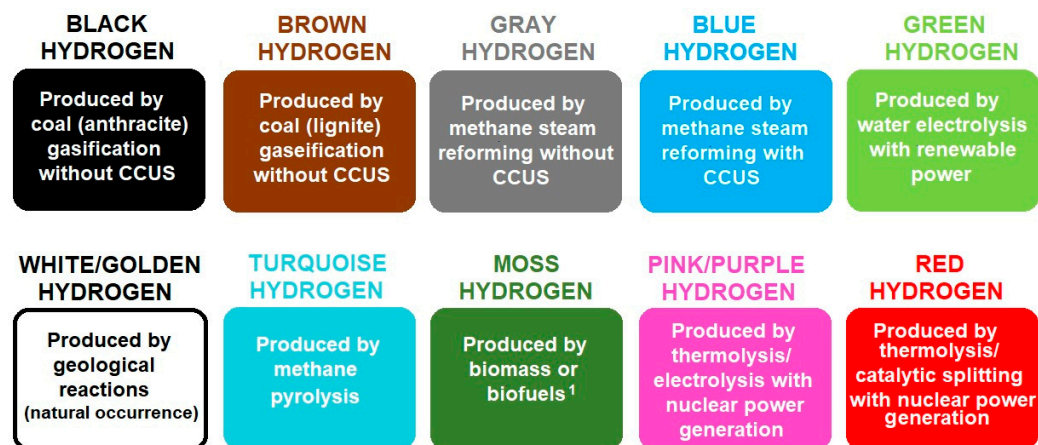


Figure 4. Basic representation of the technological paths for the production of hydrogen in Brazil. Source: Adapted from [38].

Figure 4 illustrates the many primary sources from which hydrogen can be produced, such as i. water; ii. biomass and fossils; iii. solar thermal and nuclear, among others.

Through the process of electrolysis, steam reforming, gasification, and pyrolysis, thermochemical, among others. Produced hydrogen has a variety of colors for its classification, which represent the paths for production and the range of the carbon effect [42]. Figure 5 presents the classification of hydrogen on a color scale.



¹ Via catalytic reforming or anaerobic digestions, and from gasification of plastic waste.

Figure 5. Hydrogen production-related projects in Brazil. Source: Adapted from [14,23,37,41].

The most sustainable types of hydrogen are green and blue, as shown in Figure 5. While the blue hydrogen is produced by the steam reforming process, which captures and sequesters the CO₂ produced, the green hydrogen is produced by electrolyzing water using electricity produced from renewable energy sources. Conversely, black and gray hydrogen are the most environmentally unfriendly types [27,42]. They are produced without capturing and sequestering CO₂, respectively, through gasification and from steam reforming [27,42].

It is challenging to estimate the potential cost of natural hydrogen since there are so few examples of it being harvested. According to some industry sources, it can be produced at a lower cost than the hydrogen currently produced. At an estimated cost of USD0.5 per kilogram, Hydroma, a Canadian firm, is currently harvesting natural hydrogen; however, in modest amounts [14]. Approximately USD 1 per kilogram is the target price for projects in Australia and Spain. Verification of these figures would show that natural hydrogen is reasonably priced and has competitive value [14,43].

In 2022, the amount of hydrogen produced from renewable energy sources from water electrolysis was just 0.04% of the 95 Mt of hydrogen produced [25]. Most of the hydrogen is still produced from fossil sources, with or without carbon capture [12]. The hydrogen produced from fossil sources in Brazil (gray hydrogen) costs between 1.2 USD/kg a 2.93 USD/kg, while the hydrogen produced through electrolysis (green hydrogen) currently costs between 2.87 and 3.56 USD/kg in some strategic locations [8,44–46].

Nonetheless, it is estimated that the costs related to hydrogen produced from electrolysis will reduce [8]. These rates can decrease to 1.69 USD/kg with incentives and optimizations, making them extremely competitively priced when compared to gray hydrogen, which is generated from polluting and fossil fuels [46].

3. Natural Hydrogen

Natural hydrogen is today an important subject of research from a global perspective, in the context of the energy transition [47]. Natural hydrogen, also known as white hydrogen, is formed and accumulated on Earth's subsurface after several reactions and processes [8,13,38]. This type of hydrogen, considered marginal in the past years, is increasingly emerging as an important player, gaining the attention of energy companies [48,49]. Natural hydrogen

is widely distributed in different forms, and can be encountered in petroliferous related basins, such as i. in organic-rich sedimentary basins; ii. in coal beds; iii. in fault zones; iv. associated in ultramafic rocks with extremely low crystallization and v. in potassium-bearing sedimentary strata, among others [50]. Despite being extracted from the subsurface, the origin of natural hydrogen has been described in numerous occurrences by different authors. Four main origins have been identified from the literature and detailed in Figure 6 [42]: serpentinization, radiolysis, rock fracturing, and magma degassing.

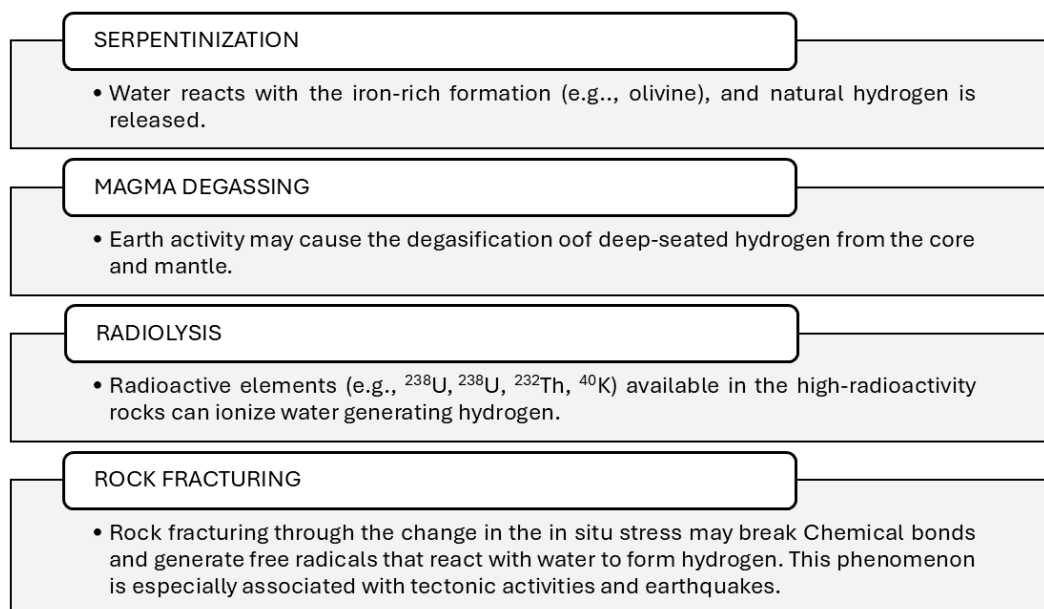
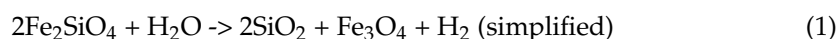


Figure 6. Four main processes of natural hydrogen generation and accumulation. Source: Adapted from [8,42,51].

3.1. Serpentinization

Understanding how it is generated and accumulated, the physicochemical processes behind it, and some other details, is very important in order to guarantee and make viable ways of accessing the related energy potentials [51,52]. Among the processes discussed, serpentinization of ultramafic rocks has been pondered as the main route of natural hydrogen production [53,54]. Since ultramafic stones, such as peridotite, which contains more than 40% olivine, make up the majority of the Earth's mantle. Serpentinization is an abiotic process that occurs in temperatures below 500 °C and involves the alteration of ultramafic rocks rich in certain minerals, for instance, olivine, in the presence of water [51,55,56]. During serpentinization, water reacts with the mineral olivine to form serpentine and hydrogen gas. This process can be summarized and represented by Equation (1) [46].



Three primary phases are typically included in the serpentinization process to produce hydrogen: Ultramafic rocks undergo (i). hydration, which releases dissolved Mg^{2+} , Fe^{2+} , and other ions; (ii). mineralization of the dissolved Mg^{2+} and Fe^{2+} , resulting in serpentine and Fe^{II} -bearing brucite; (iii). oxidation of Fe^{III} -bearing brucite, which results in Fe^{III} -bearing minerals and H_2 [53]. Serpentinization takes place in a variety of geological environments on Earth, such as mid-ocean ridges, subduction zones, and the ocean floor [55].

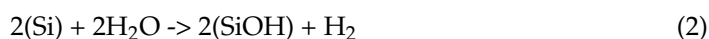
3.2. Radiolysis

The natural radioactive decay of elements like uranium (^{238}U and ^{235}U), potassium (^{40}K), and thorium (^{232}Th) is known as radiolysis [54,55]. In this process, the groundwater molecules can be broken apart to produce hydrogen and oxygen; the energy for the split came from the radioactive decay. This process was proposed by Vernadsky (1982) [42].

Water and radionuclides, two basic geological elements that are widely available on Earth, are needed for the radiolysis process to produce hydrogen [57]. Hydrogen and hydroxyl radicals are created as a result of the process, which also unites the H-O link in water. Next, hydrogen $2\text{H} \rightarrow \text{H}_2$ is created by the reaction of two hydrogen radicals [10,58,59]. Moreover, radiolysis happens at any temperature and pressure level where water is stable, regardless of whether the water is hydrated salts, steam, or ice [57].

3.3. Rock Fracturing

The process of rock fracture is caused by a shift in the in situ stress regime, which breaks chemical bonds and releases free radicals, one of which reacts with water to make hydrogen [12,60,61] (Equation (2)). This is especially associated with tectonic activities and earthquakes [51,57].



3.4. Magma Degassing

Magma degassing refers to hydrogen stemming from the center of the Earth's crust [62]. During the cooling process, the magma releases gases that can generate hydrogen. This process occurs after volcanic eruptions and in events where lava encounters seawater [57]. This process can be represented by Equation (3). The equilibrium of the magmatic carbon-oxygen-hydrogen system changes significantly at magmatic temperatures ($\sim 1200^\circ\text{C}$), suggesting that hydrogen could be a component of magma [63].



3.5. Extraction

It is known that the search for natural hydrogen requires drilling skills, techniques, and technologies similar to those applied and widely used in the petroleum industry. However, there are some differences between hydrocarbons and hydrogen systems that may be analyzed and well understood. For instance, since the lifetime of its generation would be between 10 and 100 years [47], i.e., natural hydrogen can also be considered a renewable source [64]. Another difference relates to the mobility of hydrogen throughout the rock porous medium, presenting itself to be considerably higher than the hydrocarbon [47,65].

Around the world, “fairy circles”—natural hydrogen seeps—have been spotted in a number of locations, including Brazil, Russia, Ukraine, and the United States [64,66,67]. The circular depressions that may be seen on satellite images are what define the fairy circles. In Brazil, there are expected occurrences of natural hydrogen in the states of Rio de Janeiro, Minas Gerais, Ceará, Tocantins, and Roraima [62].

Fairy circles were linked to the monitoring in the São Francisco Basin in Minas Gerais/Brazil, which reported instances of hydrogen escaping from the soil [65]. Brazil has several Proterozoic basins. The São Francisco basin is a N-S oriented structure that was formed during the Brazilian Orogeny (end of Proterozoic) and is bordered by the late Proterozoic Brasília and the Araçuaí orogenic belts. It contains rocks from Archean metamorphic basement rocks, iron-rich formations, and ultrabasic intrusions [65,66,68,69].

The existence of a commercial hydrogen play with a diameter of over 8 km has been proven by PETROMA's (now HYDROMA) recent drilling operation in the Taoudeni Basin (Mali, Africa) in 2017–2018 [64,66]. To acquire the exploration rights for the block, the

company PETROMA uncemented the water well (drilled in 1987) that had been promptly shut in and temporarily abandoned due to an unanticipated gas explosion in 2011. About five years passed during the Bougou-1 well's trial hydrogen production. Two stratigraphic wells were drilled in succession, about 100 km north of Bourakebougou. Later, a broad exploration campaign was started by drilling 18 shallow wells around the groundbreaking Bougou-1 well [13]. There are currently three available methods for the extraction of natural hydrogen from subsurface [42], detailed in Figure 7.

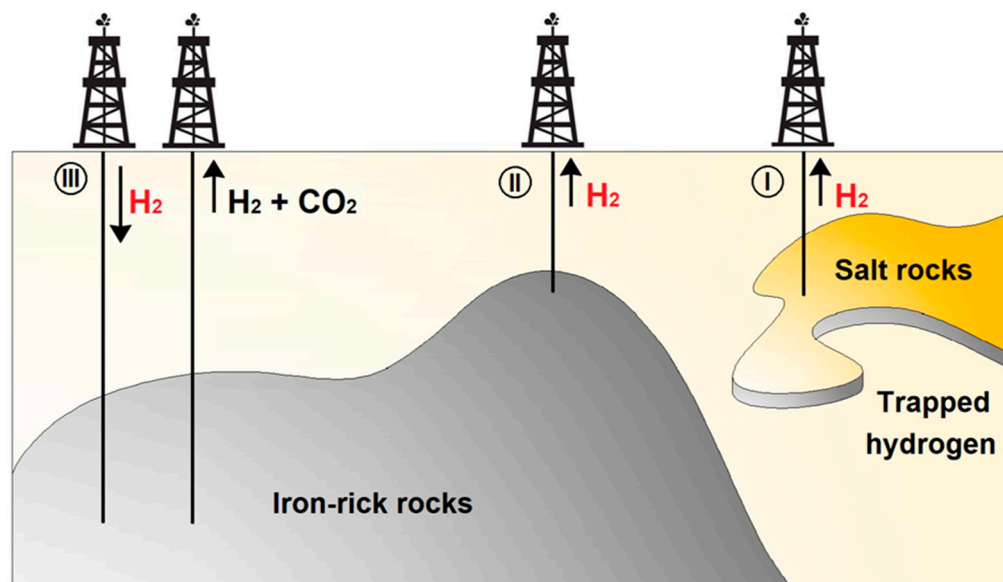


Figure 7. Schematic representation of natural hydrogen extraction. Source: Adapted from [42].

- I. Drilling a single wellbore can extract natural hydrogen that has become trapped in a subterranean space. Salt rocks and other impermeable formations can serve as cap rocks to confine natural hydrogen underneath.
- II. By drilling a single wellbore from the ground surface to the level of the iron-rich formation, the produced natural hydrogen can be collected from shallow iron-rich formations that are continuously exposed to hot groundwater.
- III. An increased hydrogen recovery method can be used in situations when there is insufficient groundwater to serpentinize the shallow iron-rich deposits. In order to create economically viable concentrations of natural hydrogen, water is pumped into the iron-rich formation from the injection well. The produced hydrogen is then drawn out of the well. For sequestration purposes, carbon dioxide can also be poured into the earth using this method.

Besides Mali, many other countries around the world also found evidence of reserves, such as Albania, Australia, France, the USA, Oman, and the Philippines, when exploring for natural gas as well as nearby geologic features like mid-ocean ridges and hydrothermal vents. In Iceland and France, H₂ generation, movement, and accumulation systems have also been reported [14,70]. Hydrogen production from subsurface hydrocarbon resources offers a promising solution for generating and extracting hydrogen underground, with thermochemical and biological methods for fossil fuel feedstocks [71]. Depleted petroleum reservoirs are increasingly used for underground hydrogen storage, with innovative methods converting fossil hydrocarbons into hydrogen-containing gas in situ, producing it in mixtures with oil, other gases, or pure form, and simultaneously using accompanying greenhouse gases [72]. However, some challenges must be overcome, like low concentration, mixing with other gases, post-processing facilities, increased costs, and resource size impacting industrialization [71].

Chemical subsurface technologies frequently use oxygen or steam injections into hydrocarbon reservoirs to initiate high-temperature reactions that yield hydrogen. Pyrolysis, reforming, partial oxidation (POX), autothermal reforming (ATR), water-gas shift (WGS), and coke gasification are typically included in the core chemical foundation. These chemical transformation processes frequently compete with one another, and the kind of hydrocarbon (oil, bitumen, coal, or gas) and the injection strategy influence which process predominates. Installing a specialized separation membrane in producing wells can improve this strategy and efficiently increase hydrogen recovery [71].

4. Materials and Methods

In this section, it is discussed the steps used to accomplish the bibliometric review on the topic of interest “natural hydrogen,” are discussed, where Figure 8 shows the step-by-step process performed. The variations to refer to this hydrogen type were used as criteria in the search of the database used, Web of Science, including “natural hydrogen” OR “geological hydrogen” OR “white hydrogen” OR “gold hydrogen”. These criteria produced, as a result, a total of 247 publications for the period 1990–2024. The next step was the refinements by adding the terms “extraction” AND “drilling”, which reduced the articles found to 205 publications. And, as a next final step, the results were filtered by country, using “Brazil” as a reference, as the Brazilian scenario perspectives of natural hydrogen exploration/exploitation are the main goal of the analyses performed. This last filter resulted in 16 publications on the subject for the given period.

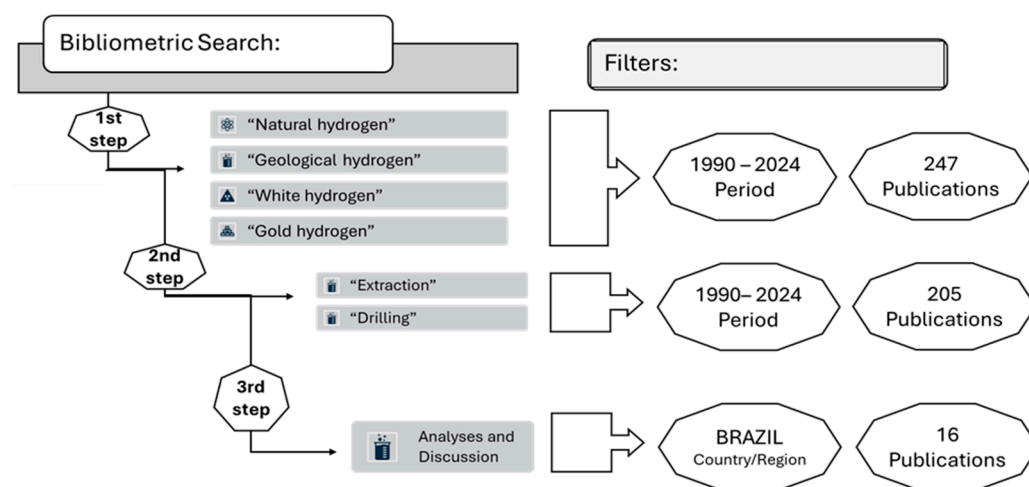


Figure 8. Stages of research and data analysis. Source: Authors (2024).

Through the data obtained by following the step-by-step methodology shown in Figure 8, it was possible to analyze the topic by: annual number of publications, publications by country, by co-authorship network, and the most recent studies on the topic. In addition, it was possible to analyze how the energy transition has been stimulating Brazilian research on natural hydrogen exploration and its potential use as an energy source.

5. Results and Discussion

Through the analysis of terms, in the database in use, the 205 articles found during the past 35 years, from 1990 to 2024, are shown in Figure 9, organized per year.

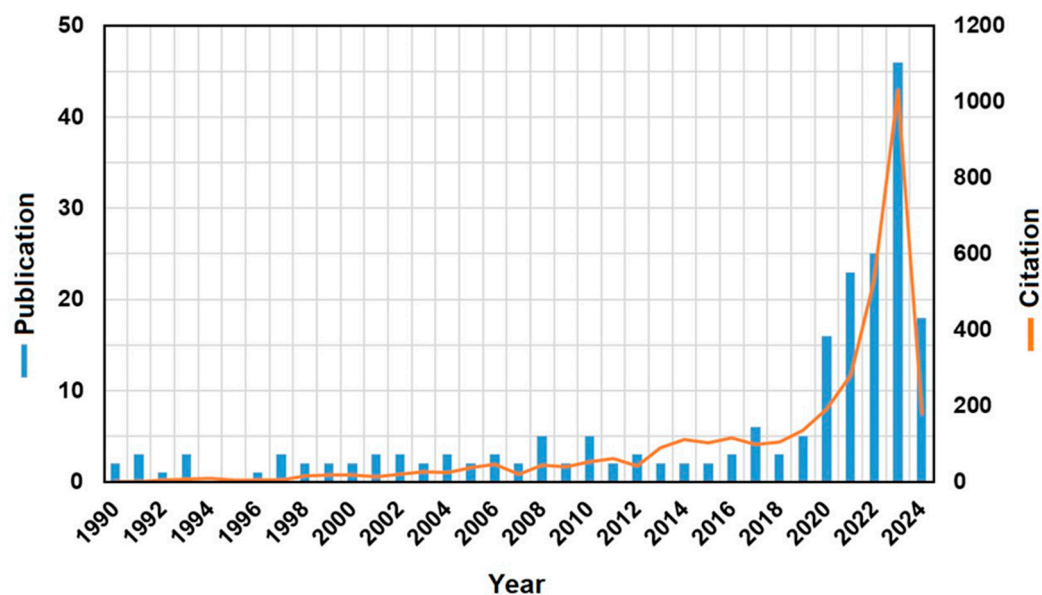


Figure 9. Number of articles published on the topic over the past years. Source: Adapted from [73].

Figure 9 shows the growth curve for the number of publications on the topic, with approximately 20 publications in the first semester of 2024. This increase in research about natural hydrogen is justified as indicated at the beginning of the paper. The researchers found out that the main related category for the articles has been energy fuels. From the graph, it is possible to identify that 2017 seems to be an important year in this context. In 2017, Japan started its development plans for the use of hydrogen. At the beginning of 2019, South Korea started its development plans, followed by Australia in the same year. In 2020, the topic gained focus and started to spread, and we can see initiatives in countries such as the Netherlands, Norway, Germany, Spain, and Portugal. In the same year, 2020, France started out, also starting strategies for hydrogen [74]. Figure 10 maps the countries that have stood out in research on the topic.

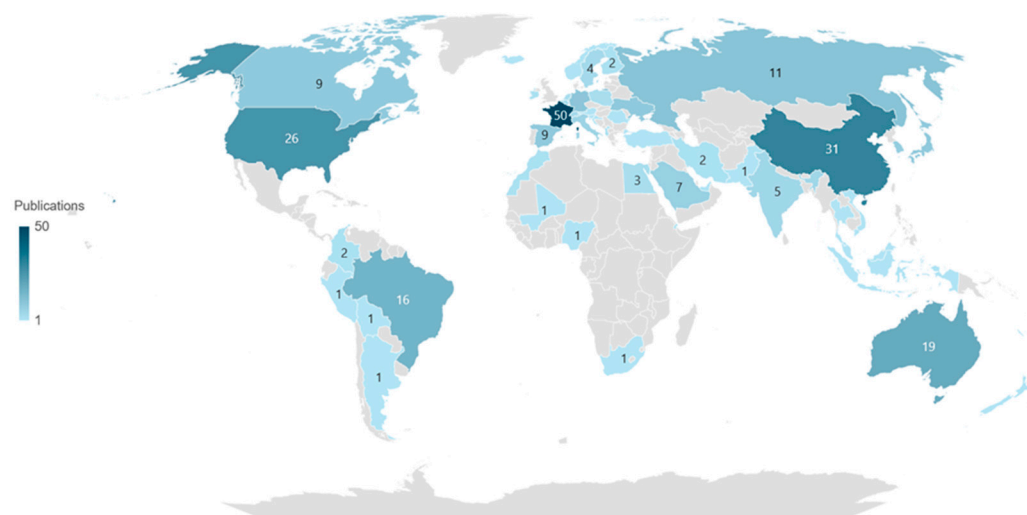


Figure 10. Number of publications by countries on the topic. Source: Adapted from [73].

As presented in Figure 10, the largest number of published articles are from researchers from France (50 publications), followed by China (31 publications), the United States (26 publications), Australia (19 publications), Brazil (16 publications), Scotland (15 publications), Russia (11 publications) and Germany (10 publications). It is worth mentioning that results concerning the extraction (well engineering, drilling) of natural hydrogen are concentrated in the Middle East region and North America.

Following the analyses, China, the United States, the European Union, India, Japan, and South Korea are the nations with the biggest demand for hydrogen in 2018 [75]. China, for example, is one of the countries that has been considerably producing hydrogen nowadays (more than 30% compared to the total global production) and hopes to reach a production of 200,000 tons per year in the near future [25].

Brazil is in the fifth position among the countries with the most publications on the subject. The recently discovered potential sources of natural hydrogen in some states, such as Goiás, Tocantins, Minas Gerais, Roraima, Bahia, and Ceará, can also partially explain the increase in the published studies. This preliminary investigation revealed a lot of promise for the discovery and exploration of natural hydrogen in Brazilian soil.

Countries are implementing public policies to promote hydrogen production chains, aiming to decarbonize economies and encourage renewable energy sources, such as hydrogen [15]. France, Germany, the Netherlands, Japan, South Korea, the USA, Australia, and Brazil are implementing these policies to support research and innovation, reduce emissions, and strengthen the hydrogen market and industry. France's Plan France 2030 aims to become a leader in decarbonized hydrogen, while the US's Public Policy for Hydrogen Development encourages research and implementation across sectors [15].

Through VOSviewer software, version 1.6.20, it was possible to obtain the co-authorship network, indicating the relationship between researchers [76]. Figure 11 shows the extended relation including subnetworks, research groups, and eventual further collaborations between.

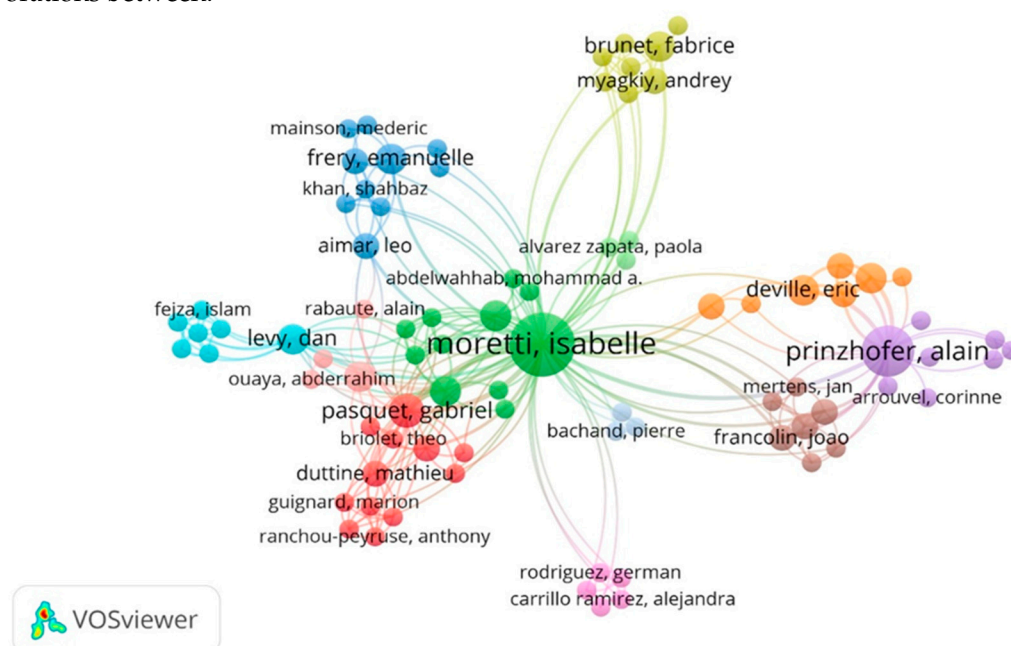


Figure 11. Authors collaborations. Source: Adapted from [73].

Through Figures 11 and 12, twelve clusters were identified, from which it is possible to highlight two of them, the researchers Isabelle Moretti and Alain Prinzhofer. They are related to 19 (nineteen) and 11 (eleven) different publications from the total research related to natural hydrogen, respectively. Also, at least one of them is connected to at least 10 (ten) of the 16 (sixteen) research papers published in Brazil between the years of 1995 and 2024.

Isabelle Moretti is now leading a team dedicated to natural hydrogen at Pau University (UPPA), where she is working on different case studies such as Brazil, Australia, Namibia, the Afar area, and Iceland. Moreover, she is also on the board of EarthH2 Hydrogen, which promotes the natural hydrogen E&P in Europe [77].

Alain Prinzhofer, after 3 years in the O&G company HRT (Brazil), created the service and research company GEO4U (Brazil). Currently, he works on the geochemistry of natural gas in general, but his main interest is now the exploration of natural hydrogen [78]. The most cited research is shown in Table 1, after adding the filter: country (Brazil) to the results.

Table 1. Most cited research.

Article Title	Journal	Year	Reference	N° Citation
Discovery of a large accumulation of natural hydrogen in Bourakebougou (Mali)	International Journal of Hydrogen Energy	2018	[64]	95
Natural hydrogen continuous emission from sedimentary basins: The example of a Brazilian H ₂ -emitting structure	International Journal of Hydrogen Energy	2019	[68]	73
The association of natural hydrogen and nitrogen: The ammonium clue?	International Journal of Hydrogen Energy	2024	[79]	61
Possible pathways for oil and gas companies in a sustainable future: From the perspective of a hydrogen economy	Renewable and Sustainable Energy Reviews	2022	[80]	53
Characterization of the spontaneously recharging natural hydrogen reservoirs of Bourakebougou in Mali	Scientific Reports	2023	[81]	35
Long-term monitoring of natural hydrogen superficial emissions in a Brazilian cratonic environment. Sporadic large pulses versus daily periodic emissions	International Journal of Hydrogen Energy	2021	[65]	29
Hydrogen Emanations in Intracratonic Areas: New Guidelines for Early Exploration Basin Screening	Geosciences	2021	[82]	25
H ₂ dynamics in the soil of a H ₂ -emitting zone (Sao Francisco Basin, Brazil): Microbial uptake quantification and reactive transport modeling	Applied Geochemistry	2020	[83]	20
Genesis of natural hydrogen: New insights from thermodynamic simulations	International Journal of Hydrogen Energy	2021	[84]	15
What Pulsating H ₂ Emissions Suggest about the H ₂ Resource in the Sao Francisco Basin of Brazil	Geosciences	2020	[85]	15
Reduction in deuterium content in carbon targets for ¹² C + ¹² C reaction studies of astrophysical interest	The European Physical Journal A	2018	[86]	15
Water behavior in the neighborhood of hydrophilic and hydrophobic membranes: Lessons from molecular dynamics simulations	Physica A: Statistical Mechanics and its Applications	2009	[87]	8
Trapping processes of large volumes of natural hydrogen in the subsurface: The emblematic case of the Bourakebougou H ₂ field in Mali	International Journal of Hydrogen Energy	2024	[9]	2
Natural hydrogen and blend gas: a dynamic model of accumulation	International Journal of Hydrogen Energy	2024	[47]	2
Hydrogen storage in depleted offshore gas fields in Brazil: Potential and implications for energy security	International Journal of Hydrogen Energy	2023	[88]	1
Analysis and Multi-Objective Optimization of the Rate of Penetration and Mechanical Specific Energy: A Case Study Applied to a Carbonate Hard Rock Reservoir Based on a Drill Rate Test Using Play-Back Methodology	Applied Sciences	2024	[89]	1

Source: Adapted from [73].

The list of research presented in Table 1 may represent the interest of several researchers, including Brazilians, in the area concerning natural hydrogen and related access (well engineering, drilling). In this context, several developments and achievements driven by Alain Prinzhofer have shown interesting results. Show how hydrogen has been detected on the surface (or shallow subsurface), and details studies on their levels of avail-

ability, providing a way to further determine if a potential for exploration may exist or not [9,47,64,65,68,79,81,82,84,85].

Other studies like the ones conducted by Isabelle Moretti have analyzed the escaping and mobility of hydrogen from sedimentary basins, identifying and monitoring the formation identifying the so-called “fairy circles”. These analyses were performed at the Sao Francisco Basin and in the State of Minas Gerais, in Brazil. Also very important to mention, that one of the articles highlight the need to improve the drilling process, once natural hydrogen exploration necessitates expertise equivalent to the oil and gas sector; and a second one, assesses the feasibility of storing hydrogen in Brazil’s depleted offshore gas reserves and the potential implications for national energy security [65,68,82,83].

Brazil has as much potential for renewable energy as its size. COPPE/UFRJ professor Maurício Tolmasquim demonstrated this in his opening presentation for the plenary cycle of the World Hydrogen Energy Conference [90], which was held in Rio de Janeiro in June of that year. According to [90], compared to global data from 2003, Brazil already had 78.2% of renewable energy production, of which 68.2% is hydraulic (more than 60%, representing twice the consumption of Brazilian homes)—compared to 22.2% in the rest of the world. This placed Brazil in first place as a country with a high potential to migrate to the current best energy alternative: hydrogen [90].

Hydrogen exploration in Brazil is at an embryonic stage, with no commercial discoveries. However, research shows evidence of hydrogen in the Araguaia Belt in Tocantins; Magnetic anomalies and evidence of hydrogen in Ceará; In Bahia, Petrobras has been carrying out research work on hydrogen generation and extraction since 2023; the San Francisco basin, the subject of many of Prinzhofer’s and Moreti’s studies, has an estimate of a daily emissions of 1 m^3 per m^2 pulsing in cycles detected by the company ENGIE; The Parecis Basin has flammable exudations in Neoproterozoic rocks indicating the presence of hydrogen; however, the region still lacks more studies and measurements. In the Paraná basin, several origins for hydrogen arise, including radiolysis, rock alterations, mantle source, and maturation of organic matter; and finally, Maricá presented through perforations in 2022–2023 production of natural hydrogen formed by radiolysis between water and rocks in situ [15,65,68,83,91–94].

To achieve a sustainable transition to hydrogen exploration/exploitation, remodeling is necessary, connecting hydrogen production plants and public policies to achieve this goal. Figure 12 shows the timeline of the steps that have been initiated in Brazil about the use and applicability of hydrogen in national soil, from 1995 to today.

As it is considered an energy vector, hydrogen production has several routes, such as steam reforming of biomethane, acidogenesis, geological, among others. From 1995 to 2005, Brazil has been focused on the development of Fuel Cell Programs. However, with the discovery of the pre-salt reservoir potential (around 2006), it was observed that there was a gap of four years without any development in public policies on hydrogen. With the Pre-salt discovery, there was a big opportunity for the Brazilian government to achieve independent production of fossil fuels. This subject gained all the attention for the first years of its exploration. With the fossil fuels technologies and challenges of pre-salt exploration overcome, the government once again focused on diversifying the energy matrix. In 2010, the hydrogen energy plan of subsidies for competitiveness policies was published for the subsequent 15 years. The next milestone on the timeline was the development of the National Energy Plan 2050 (PNE 2050), which points to hydrogen as a disruptive technology and as an element of interest in setting up the decarbonization of the energy matrix.

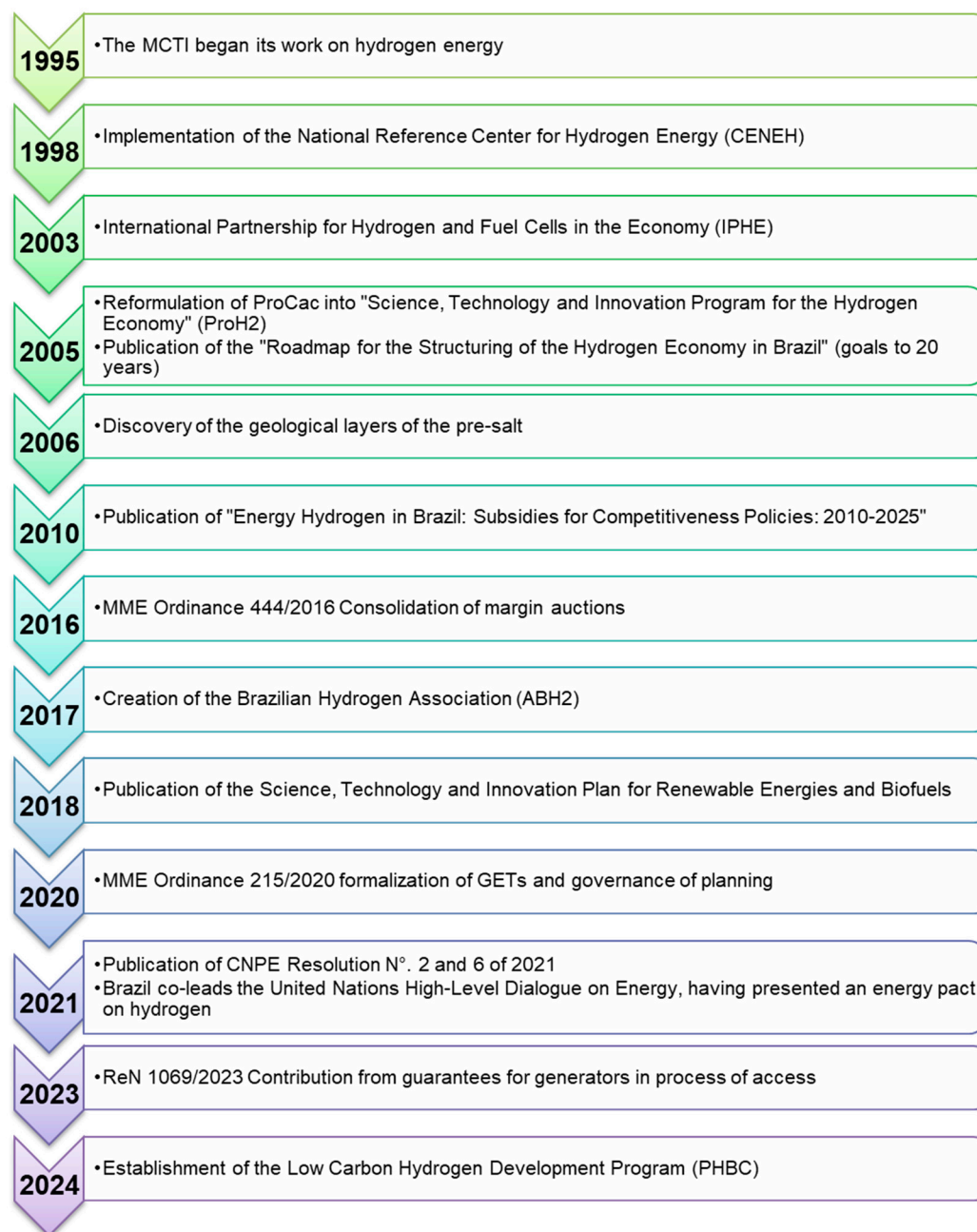


Figure 12. Timeline of hydrogen-related energy in public policies in Brazil. Source: Adapted from [95–98].

Even though hydrogen has been a subject of study for over 20 years, just recently, there has been a more consistent movement to make sure it is implemented in the national energy matrix, as a cleaner and environmentally friendly energy source (or energy vector). From 2016, it can be observed on the timeline that the first steps were taken to consolidate projects around the national margins. With the consolidation of public policies, since 2021, Brazil has 31 projects in progress, at pilot-scale, and industrial-scale projects have been announced. The technical potential of hydrogen production expected from these projects is 7,747,333 tons of renewable H_2 /year. From the implemented projects, the current expected production of green hydrogen is as follows per source of electricity: wind energy (8.12%); hydroelectric power (40.06%); photovoltaic plants (3.97%); and biomass (47.85%).

Natural hydrogen is still in the monitoring phase in Brazilian soil, and one can emphasize that at least four states have potential reserves: Ceará, Roraima, Tocantins, and Minas Gerais. The research is not able to estimate production from this source at this

moment [90,99,100]. Table 2 presents a SWOT (Strengths, Weaknesses, Opportunities, and Threats) matrix analysis. Since their introduction by Albert Humphrey in the 1960s, SWOT assessments have gained significant popularity as a valuable tool for strategic development and decision-making [101]. With considerable strategic techniques with two key steps [102,103], it operates by assessing both external (such as “opportunities” and “threats”) and internal (such as “strengths” and “weaknesses”) variables. It has been applied to natural hydrogen cases in Table 2.

Table 2. SWOT analysis.

Strengths	Weaknesses
- Natural and potentially renewable source: Produced through ongoing geological processes. - Low carbon emissions: Can be extracted with reduced environmental impact. - Availability of unexplored areas: Potential for discovering new accumulations and reservoirs. - Versatile applications: Applicable in energy generation, the transportation sector, and chemical industries. - Leverages existing infrastructure: Adapts technology from hydrocarbon-related industries.	- Limited knowledge base: Less studied in place when compared to hydrocarbons. - Hydrogen volatility and diffusivity: Challenges exist and are mostly related to storage and transportation. - Underdeveloped extraction technologies: Methods for accessing and producing are still evolving. - Operational risks: Hydrogen’s reactivity poses challenges during drilling and production activities. - High initial costs: Significant investment in RD&I and also for infrastructure is required.
Opportunities	Threats
- Energy transition: Aligned with global decarbonization efforts and goals. - Government support: Public policies promoting clean energy sources. - Technological advancements: Development of new extraction and storage methods. - Investment in clean energy: Growing interest from companies and investors in the sector across the globe. - Regional energy diversification: Strategic resource for areas without hydrocarbons.	- Competition from other hydrogen sources: Green and blue hydrogen are advancing rapidly. - Regulations and permitting: Environmental and regulatory constraints could delay projects. - Geological uncertainty: Identifying economically viable reservoirs remains challenging. - Local environmental concerns: Risks of contamination and eventual seismic activity. - Energy market volatility: Fluctuations in terms of fossil fuels and/or renewable energy-related prices may impact overall competitiveness.

Source: Authors (2024).

Natural hydrogen offers a number of research and development opportunities that can support Brazil’s (and other countries’) energy transition, as seen in Table 2. Natural hydrogen has been seen as an opportunity for many startups, due to its economic viability and considerable potential seen across the globe. Even though many regions in Brazil haven’t been studied, the potential is considered to be interesting. Natural hydrogen is not as pure as the hydrogen produced by other processes, but it can be purified with some applied technologies already known and developed. Large companies and governments of several countries have been cautious regarding the research and development of this energy source. The legal path to exploitation and regulation has yet to be exhaustively discussed and developed. Different from fossil fuels that take millions of years to form and that are related to greenhouse gas emissions, the natural hydrogen generation process is an ongoing flow and environmentally friendly. The costs of production of hydrogen from natural reserves are expected to be cheaper than those from other routes.

6. Conclusions

In the presented technical-scientific research, a review across topics involving natural hydrogen was performed. The following are the most significant results drawn from the presented study:

- In 2022, the global use of hydrogen was 95 Mt and is expected to reach, by 2030, more than 150 Mt.
- Projections show that in 2030, hydrogen will be intensively used in different processes and activities: processes of refining (37.0 Mt), ammonia (34.5 Mt), methanol (17.1 Mt), steel (12.7 Mt), and others (51.0 Mt). Additional uses include power generation, transportation, buildings, and high-temperature industrial heat.
- Over USD 25 billion has already been announced for investments in green hydrogen generation plants in Brazil. The Port of Pecém (Ceará), Port of Suape (Pernambuco), and Port of Açu (Rio de Janeiro) are the main locations for investments.
- The projects in Brazil will produce a total of 12,921 MW and 2237 Kt/year of green hydrogen by 2030.
- The growing research in Brazil is explained mainly due to the potential of natural hydrogen sources being studied in the São Francisco Basin and states such as Goiás, Tocantins, Minas Gerais, Roraima, Bahia, and Ceará, as well as due to the successful exploration of Bourakebougou (Mali) and more recently to the Albanian discovery.
- The main origins proposed for natural hydrogen are serpentinization, magma degassing, radiolysis, and rock fracturing.
- Direct drilling of iron-rich rocks or deposits trapped by salt layers can be utilized to recover natural hydrogen, which is a technique similar to that already employed in the oil and gas sector.
- The number of hydrogen research studies presented an exponential growth curve in recent years, also due to the search for energy security and diversification global energy matrix.
- The countries in which researchers published on the topic were France, China, the United States, Australia, Brazil, Scotland, Russia, and Germany, respectively.
- Because there are so few examples of natural hydrogen being produced, it is difficult to assess its potential cost, but it is expected to have a lower cost when compared to green hydrogen.
- The Hydroma industry estimates natural hydrogen costs at 0.5 USD/kg, while projects in Australia and Spain have approximately 1 USD/kg as a target price. Since drilling is the most prevalent method of securing access to these energy-related natural resources, it is essential to maintain a transfer of knowledge and technology from the oil and gas business to the hydrogen industry in order to access natural hydrogen accumulations.
- Estimates indicate that natural hydrogen can supply global energy demand for centuries, facilitating the decarbonization of the energy sector. However, there are uncertainties, such as the need to better understand the geological processes that govern the generation of natural hydrogen, the behavior of reservoirs over time, and the effectiveness of extraction technologies.
- In Brazil, more geophysical and geochemical studies are needed to confirm the viability of these reserves.
- The discovery of natural hydrogen will also require a solid regulatory framework and a dialogue between government, companies, and society to make its exploitation viable. The potential is great, but the technical and regulatory challenges require collaboration for sustainable exploration.

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