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Energy Technology Transition Through Geological Hydrogen: Patentometric Analysis of Deposits in Brazil Between 2016 And 2026

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Abstract

Geological hydrogen has emerged as a strategic alternative in the global energy transition and decarbonization agenda. This study aims to analyze the technological panorama of geological hydrogen through a patentometric approach, based on data extracted from the Espacenet database, considering the period from 2016 to 2026 and Brazil as a protection territory. The final sample comprised 322 patent documents, analyzed according to variables such as temporal evolution, geographic distribution, applicants, inventors, IPC classification, language, legal status, and legal situation. The results indicate a technological field in a consolidation phase, with stable patenting activity between 2016 and 2022, followed by an apparent decline in recent years, mainly associated with the 18-year confidentiality period of patent publication. A strong concentration of both inventive capacity and ownership was observed in the United States of America, while European countries form a relevant secondary pole of innovation. Brazil stands out as a strategic protection market, although with limited participation in the generation and appropriation of knowledge. From a technological point of view, the main applications are associated with the oil and gas industry, particularly in the exploration, monitoring, and recovery of fluids. However, there is a growing convergence with chemical, electrochemical, biotechnological, and environmental processes, evidencing the interdisciplinary nature of the area. The innovation framework reveals a concentrated pattern, dominated by large multinational corporations, coexisting with a broad base of independent inventors and smaller organizations. In addition, the comparison between the inventing and requesting countries exposes structural asymmetries in the appropriation of knowledge, especially in emerging economies. It is concluded that geological hydrogen constitutes a strategic and consolidating technological field, with high potential to contribute to energy security and emission reduction, although still marked by structural inequalities in the global distribution of innovation.

***Keywords**: Decarbonization, Energy transition, Intellectual Property, Technological innovation.*

INTRODUCTION

Climate change imposes a global urgency for the diversification of energy sources, prioritizing cleaner and more sustainable alternatives, with a view to mitigating emissions of polluting gases. In this context, hydrogen stands out as a promising alternative, due to its high energy density per unit mass [1], [2], [3], [4], [5], [6].

The identification of hydrogen was made by Henry Cavendish, in 1766, when he observed the release of a flammable gas during reactions between acids and metals. Later, in 1783, Antoine Lavoisier recognized it as a chemical element, calling it "hydrogène", a term that means "generator of water". It is the lightest and most abundant element in the universe, generally associated with other elements, representing approximately 90% of the total number of atoms and about 75% of the mass, being the main fuel for nuclear fusion reactions [5], [6], [7].

Hydrogen (H_2) is a strategic and priority energy vector in the transition to a low-carbon economy, especially in sectors that are difficult to decarbonize, such as transport and industry, which still depend mostly on fossil fuels. Its use contributes to meeting two central requirements of the Paris Agreement: energy security and the reduction of greenhouse gas emissions [5], [6], [8], [9], [10], [11], [12].

Under normal conditions, hydrogen is a colorless, odorless, tasteless, and non-toxic gas, characterized by a high energy density by mass. These properties make it a promising alternative for the generation of electrical and thermal energy, with low or no emission of pollutants, positioning it as one of the main candidates for replacing fossil fuels [6], [7], [13], [14], [15], [16].

The European Commission (2020) classifies hydrogen according to its production process, covering the following categories: hydrogen based on electricity; renewable; clean; based on fossil fuels; fossil-based with carbon capture; low-carbon; and synthetic fuels derived from hydrogen [17], [18].

The production of hydrogen can be carried out through various technologies, with water electrolysis being one of the most relevant. This process consists of the decomposition of the water molecule (H_2O) into Hydrogen (H_2) and Oxygen (O_2), through the application of electrical energy, whether or not from renewable sources [5].

The applications of hydrogen are wide, highlighting its use in industry, especially in oil refining, ammonia production, and in the process of industrial decarbonization. In addition, it is used as fuel in rockets and space propulsion systems [6], [15], [16].

Several methods exist for storing hydrogen gas, such as in abandoned oil fields. Liquid hydrogen, after compression and cooling, can be stored in special containers with adiabatic vacuum insulation. Among the advantages of liquid hydrogen over gaseous hydrogen, the higher volumetric energy density stands out, however, its liquefaction process has high energy consumption, high cost, and risk of leakage. In turn, the storage of hydrogen in the solid state is carried out through physical or chemical adsorption [19], [20], [21], [22], [23].

Currently, several countries have intensified investments in research and development (R&D) for the consolidation of a hydrogen-based economy, through the implementation of public policies and demonstration projects that cover the entire value chain of this energy vector [7], [24], [25]. Initiatives such as the Hydrogen City Projects program, in the Republic of Korea [26], Germany's National Hydrogen Strategy in 2020, India's National Hydrogen Roadmap in 2006, and the U.S. National Hydrogen Strategy and Roadmap in 2023 [27].

Companies in the oil sector have directed efforts to rebuild reserves and diversify their portfolios, incorporating low-carbon energy sources, with the aim of mitigating the impacts of global warming. This sector is relevant in the expansion of the market, as it has infrastructure, inherent technical capacity, and capital resources [2], [6], [28], [29], [30], [31].

In Brazil, PETROBRAS, the country's main supplier of primary energy, has taken a prominent role in reducing polluting gas emissions, expanding its operations in the integration of renewable energies and strengthening initiatives aimed at the decarbonization of its energy matrices [6], [31], [32].

Brazil has high potential to consolidate itself as an important *player* in hydrogen production, due to its diversified energy matrix, with emphasis on wind, solar, and hydraulic sources; in addition to the use of biofuels; biomass, and agricultural waste [7], [33], [34], [35]. Added to this scenario is the regulatory framework of the Brazilian Electric Sector, which makes it possible to meet domestic demand and export energy surpluses. However, the consolidation of this market depends, among other factors, on the training of qualified human resources and the strengthening of investments in R&D [18].

In Brazil, hydrogen occurrences have been identified in different geological regions, including the São Francisco Basin; the Ribeira Strip (Maricá, RJ); the Paraná Basin; the Parecis Basin, in Mato Grosso; the Araguaia Belt, in Tocantins; and the Borborema Province [6], [33].

Geological hydrogen – also called natural, golden, geogenic or white – is not produced by biological activity, but is found in natural reservoirs formed by geological processes, such as water-rock interactions, microbial activity, and mineral reactions. Its applications involve underground storage, natural production, and capture with subsequent injection into geological formations, configuring itself as an emerging field of research and technological innovation [6], [19], [36], [37], [38].

The first recorded occurrence of evidence of natural hydrogen dates back to the 1970s. Subsequently, with the improvement of the probes from 1997 onwards, the French

Institute of Marine Development carried out explorations with underwater robots 2,300 meters below the surface, on the Atlantic Ridge, south of the Azores, where seven natural hydrogen escape points were identified. In other regions, Russian, Japanese, and American scientists have also made similar discoveries [19].

There are more than 30 distinct processes used in the production of hydrogen gas, however, the main sources of obtaining geological hydrogen are serpentinization, through the hydrothermal alteration of peridotite, a process that involves interrelated reactions of dissolution-precipitation, redox reactions, and hydrogen formation. In this context, hydrogen generation occurs when water is reduced during the oxidation of ferrous iron to thermal iron [19], [39], [40].

Another relevant route is the production of hydrogen by radiolysis, which occurs during the breakdown of the water molecule as a result of radioactive decay. This process is promoted by the radiation released by the decomposition of radioactive elements – such as uranium, thorium, and potassium – present in marine rocks, leading to the ionization of water and the formation of free radicals that contribute to the generation of hydrogen [19], [39].

Additionally; Hydrogen can be generated by fracturing rocks on wet surfaces of active faults. In this case, the breaking of chemical bonds promotes the formation of free radicals, which react with water, resulting in the formation of hydrogen [19], [39], [40].

Patent documents provide relevant information about the inventive step, including the location of its occurrence, the technologies used, and the geography of intellectual property appropriation, as well as indicating technological leadership.

In this context, technological prospecting based on patent analysis is a strategic tool to map scientific advances, identify relevant actors and priority areas for investments, in addition to subsidizing the formulation of public policies and business strategies.

In view of this, the present study aims to carry out a patentometric analysis of geological hydrogen, investigating the panorama of patents related to the terms *Hydrogen AND Geological*, filed in Brazil in the period from 2016 to 2026, using the Espacenet database.

METHODOLOGY

The research adopted a methodological approach of a basic nature, with a descriptive and exploratory character, aiming at both the expansion of scientific knowledge and the in-depth investigation of the phenomenon studied. Exploratory research seeks to examine a specific theme in order to understand its causes and relationships [41], [42].

The technical procedure used was bibliographic, based on the critical analysis of the existing academic production, which allowed the researcher to contextualize the study within the scope of previously consolidated scientific knowledge [41].

Regarding the nature of the approach, the research is characterized as qualitative, as it does not employ statistical methods in data analysis [41]. Documentary sources in physical and digital support were used, including course completion works (theses, dissertations, and monographs), academic articles, institutional and government websites, as well as patent documents. The databases used to search for scientific literature were the CAPES Journal Portal, Web of Science (WoS), Google Scholar, SciELO, and Scopus. The keywords were defined based on the research theme, using the combination "Hydrogen AND Geological".

The study also has an applied character, by using the patentometric approach as a tool for technological analysis, allowing the identification of trends, relevant actors, and innovation dynamics [41].

The technological prospecting was carried out on April 23, 2026, in the Espacenet database, through the combination of the terms "Hydrogen AND Geological", initially resulting in 22,440 documents, with records from 1866 onwards. For the purposes of analysis, the time frame from 2016 onwards was delimited. Subsequently, the selection of documents filed in Brazil, in the period from 2016 to 2026, was applied as a filter, totaling 322 patent documents.

The collected data were organized in Microsoft Excel spreadsheets and submitted to analytical treatment, with a view to generating graphic representations and systematizing the results.

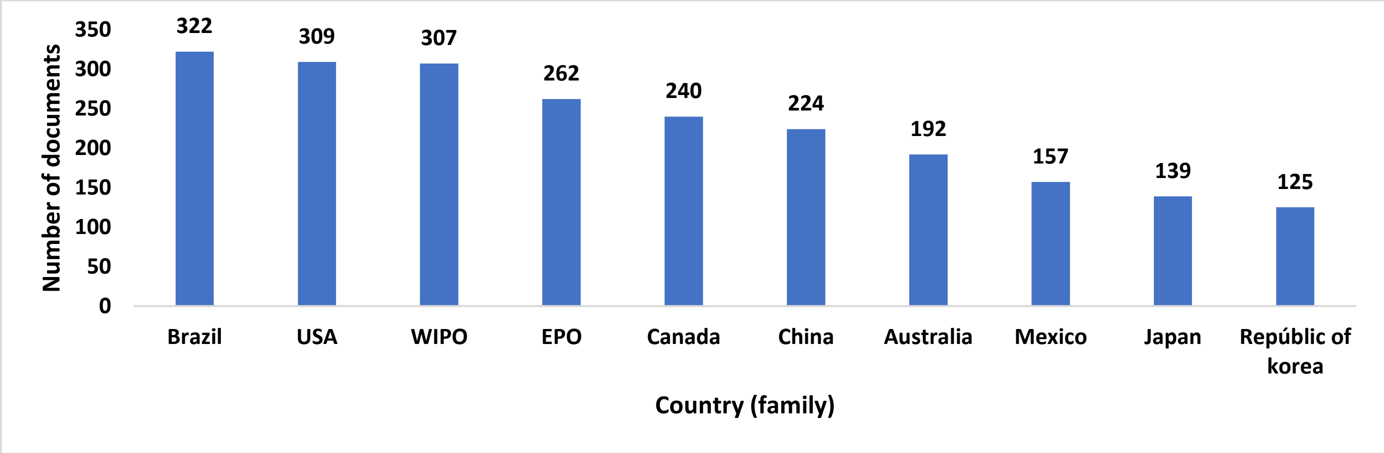
The variables analyzed included: temporal evolution (year of publication and priority), ownership, inventors, legal status, legal status, language of documents, classification according to the International Patent Classification (IPC), country of origin of applicants and inventors, as well as the analysis of technological and geographic trends.

RESULTS AND DISCUSSION

GEOGRAPHICAL DISTRIBUTION

The geographical distribution of the patent families related to the theme "Hydrogen AND Geological" aims to identify the relevant patterns associated with technological internationalization, strategic markets and innovative leadership, as shown in Figure 1.

Figure 1 – Geographical distribution of patent families



Source: Authorship (2026)

Figure 1 shows that Brazil, the reference country of the search, is configured as the main protection territory, an expected result due to the filter applied in the search strategy. The interest in protecting technologies in the country suggests recognition of the national geological potential, especially with regard to underground storage and natural hydrogen. Such a move can be interpreted as a marketing strategy, in addition to indicating Brazil's growing relevance in the green hydrogen and energy transition agenda. It should be noted that the fact that a patent is part of a family with protection in Brazil does not necessarily imply that the technology has been developed in the country, but rather that it has been selected as a strategic market for commercial exploitation.

The patent offices with the highest representation were the United States of America (USA), with 309 documents; the World Intellectual Property Organization (WIPO), with 307 documents and the European Patent Office (EPO), with 262 documents, highlighting the high global strategic value of these technologies.

The expressive use of the WIPO office indicates that applicants resort to the Patent Cooperation Treaty (PCT) as a mechanism to expand the international protection of their inventions, which reinforces the emerging and competitive character of this technological field.

Countries such as Canada (240 documents) and Australia (192) also stand out, due to their favorable geological formations and their investments in energy, factors that drive the protection of technologies related to geological hydrogen.

In Latin America, Mexico (157 documents), Colombia (36), Argentina (33), Chile (30), and Peru (17) are present, which highlights the growing relevance of the region in the expansion of technological protection. This scenario suggests strategic interest in areas with geological and energy potential, and may also reflect strategies for insertion in emerging markets and the creation of technological niches.

European countries have lower individual representation, not being among the top ten. This result is largely due to the use of the centralized system of the European Patent Office, which consolidates filings at the regional level.

In addition, 22 countries were identified with low frequency of publications, ranging from one to ten documents, which may indicate less strategic markets, lower capacity for technological absorption and reduced exploratory interest on the part of applicants.

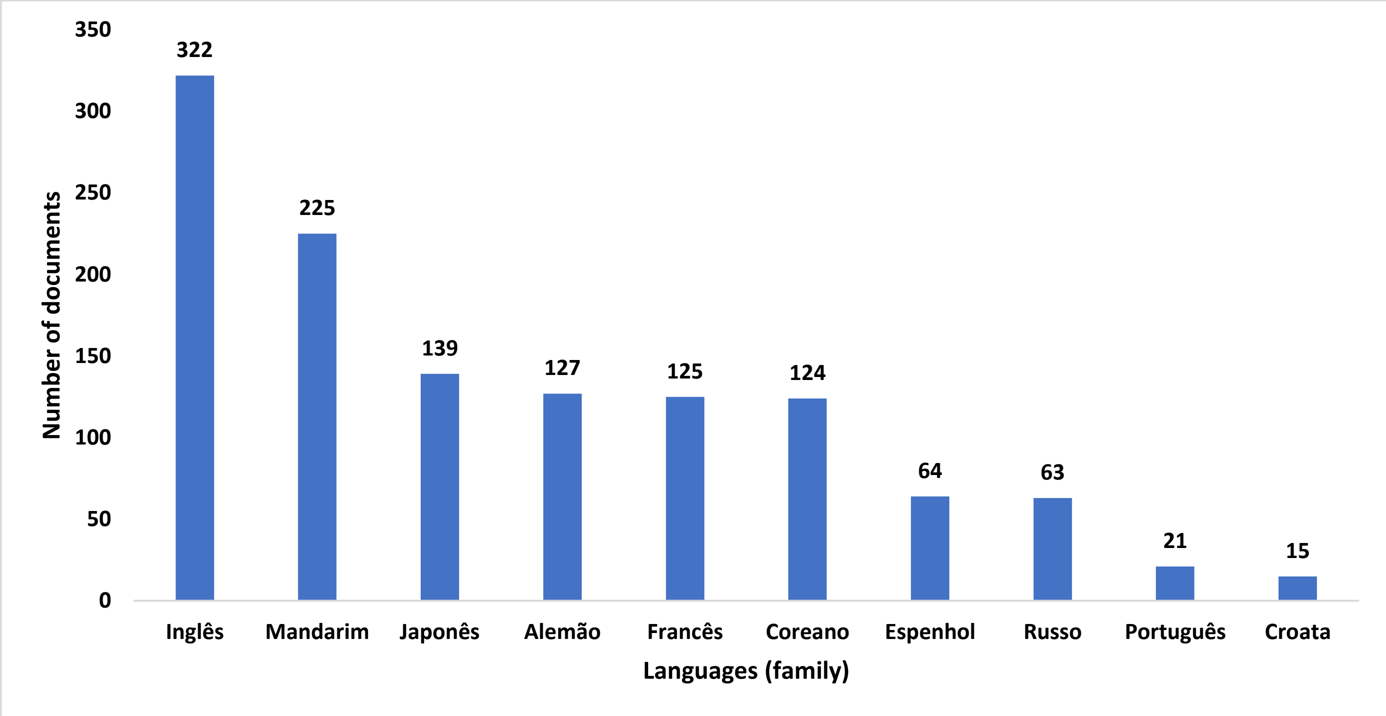
In general, the geographical distribution reveals three central aspects: (i) strong technological internationalization, evidenced by the simultaneous presence of jurisdictions such as China, Europe, and the USA, indicating a highly competitive environment; (ii) relevance of the geological factor, which is decisive for countries that have the potential for geological hydrogen storage, exploration of natural hydrogen and energy infrastructure, which are essential factors for the concentration of more deposits; (iii) Brazil's leading role as a key market, whose leadership suggests only regulatory activity and potential for green hydrogen projects, but also growing international interest in the exploration of its natural resources.

Therefore, the analysis of the distribution of patent families shows a global strategy of technological protection, with concentration in developed economies and countries with high geological potential. Brazil's prominence, combined with the strong presence of deposits via the PCT system and in jurisdictions such as China, Europe, and the USA, reinforces that technologies related to geological hydrogen constitute an emerging field of high strategic value, with direct implications for the energy transition and global energy security.

LANGUAGE OF DOCUMENTS

The languages in which patent documents of the same family are published or made available are a relevant indicator to understand the strategies of internationalization, accessibility, and definition of target markets of technologies related to the theme, as shown in Figure 2.

Figure 2 – Language of Patent Documents



Source: Authorship (2026)

Figure 2 shows the predominance of English (322 documents), consolidating itself as the main language of global technological communication. This condition expands the international reach of inventions, facilitates the dissemination of technical knowledge and favors protection in multiple jurisdictions.

Other highly represented languages include Mandarin (225 documents), Japanese (139), German (127), French (125), and Korean (124), reflecting the strong participation of technologically advanced countries. This scenario indicates that these countries not only lead technological development, but also maintain patent documentation in their national languages. In the case of German and French, there is an association with the European Patent Office (EPO) system. In addition, the significant presence of Asian languages highlights the continent's leading role as a central hub of innovation in the hydrogen sector.

Among the languages of intermediate representativeness, Spanish (64 documents), Russian (63), and Portuguese (21) stand out. Spanish reflects the performance of Latin American markets and Spain, while Russian indicates the participation of Eastern European and Eurasian countries. Portuguese, in turn, reveals that, although Brazil stands out as a territory of patent protection, most documents are not written in that language, but in English. This fact demonstrates the limited relevance of Portuguese as a language of technological dissemination on a global scale.

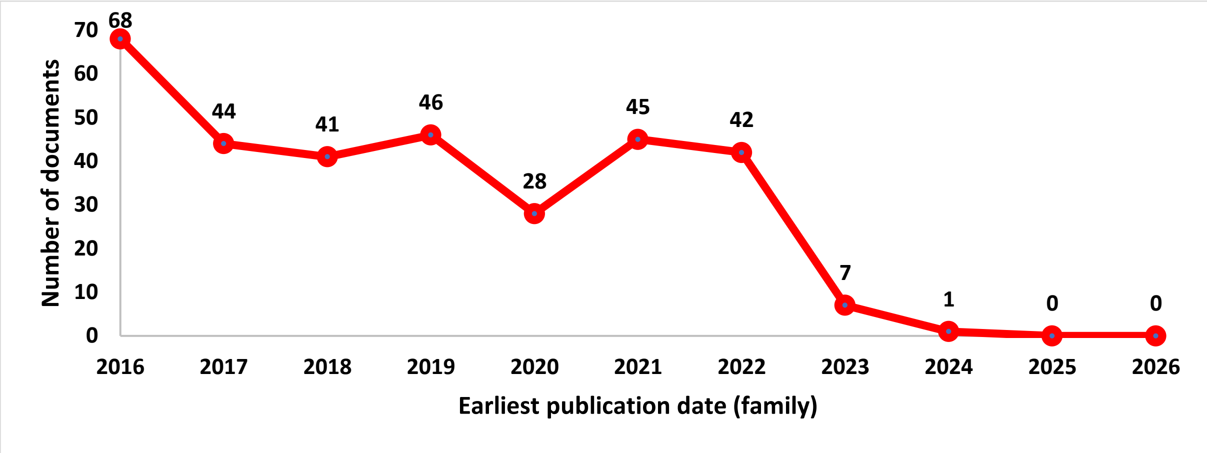
Low-frequency languages, such as Croatian (15 documents), Serbian (12), Ukrainian (8), Italian (3), Norwegian (3), Danish (1), and Swedish (1), suggest that filings are concentrated in specific national or regional contexts, with a lower degree of internationalization and marginal participation in the global innovation landscape.

Therefore, the linguistic distribution of patent families shows the predominance of English as the lingua franca of innovation, associated with technological internationalization strategies. The significant participation of Asian languages, such as Chinese, Japanese, and Korean, reinforces the role of these countries in the development of technologies related to geological hydrogen. On the other hand, the low incidence of Portuguese shows its limited relevance in the global dissemination of technological knowledge, even in a context in which Brazil stands out as a market for patent protection.

TEMPORAL EVOLUTION

The temporal evolution of patent families, between 2016 and 2026, shows the technological dynamism of the sector, as can be seen in Figure 3.

Figure 3 – Temporal evolution between 2016 and 2026



Source: Authorship (2026)

The first identified publication occurred in 1976; However, it was decided to analyze the period from 2016 to 2026, considering 2016 as the starting point of the recent activity.

Although it is not part of the time frame adopted, it is observed that the peak of publications occurred in 2012, with 115 documents, and in 2015, it was 48 documents. In 2016, there was the largest number of documents within the period analyzed (68), indicating a possible milestone of intensification of technological interest, associated with the growing relevance of hydrogen as an energy vector in the context of the energy transition.

Figure 3 shows a technological cycle characterized by growth, maturation and apparent recent decline of innovative activity in the analyzed domain. This cycle is relatively stable, without exponential growth, but with consistent behavior over the years.

Expansion and consolidation phase (2016-2019)

The initial period, between 2016 and 2019, concentrates the largest volumes of publications, with emphasis on 2016 (68 documents), possibly driven by the Paris Agreement and the increase in investments in R&D.

Between 2017 and 2019, there was stability in filings, with a variation between 41 and 46 documents. This behavior indicates continuity of global investments in R&D in energy and environmental technologies in the post-2015 context, suggesting a process of gradual maturation of technologies. In addition, it shows that the theme remained relevant, although without exponential growth.

Adjustment and recovery phase (2020-2022)

In 2020, there was a reduction in the number of publications (28 documents), possibly associated with the global impacts of the COVID-19 pandemic, which temporarily affected research, development, and patent filing activities, in addition to promoting a reorganization of technological priorities.

In the following years, 2021 (45 documents) and 2022 (42), there was a resumption and stabilization of activities, indicating the recovery of investments in innovation and the strengthening of the clean energy and decarbonization agenda. This behavior highlights the resilience of the innovative activity and reinforces the consolidation of hydrogen as a strategic technology.

Informational lag phase (2023-2026)

Between 2023 (7 documents) and 2024 (1), there was a sharp drop in the number of publications. However, this behavior does not necessarily indicate technological disinterest, and may be related to the delay in publication (delay), resulting from the secrecy period of approximately 18 months between filing and publication.

In the years 2025 and 2026, no publications were registered. This absence should not be interpreted as a reduction in innovative activity, but rather as a typical effect of the delay in the publication of patents, widely documented by organizations such as the World Intellectual Property Organization.

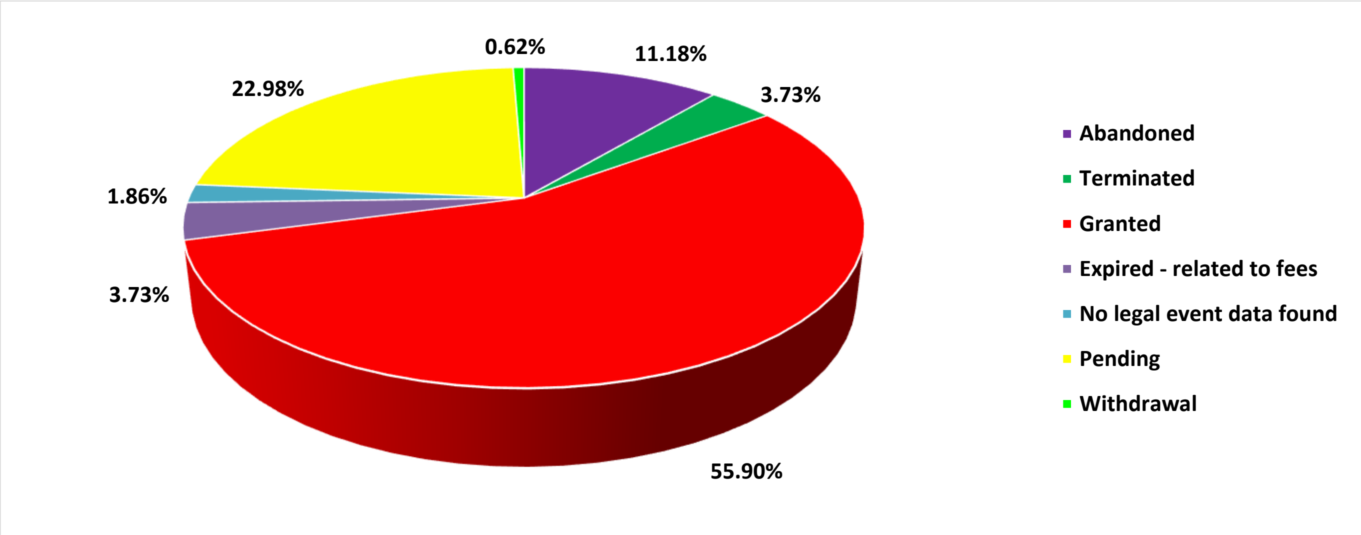
Overall, the period analyzed demonstrates sensitivity to global shocks, as evidenced by the decline in 2020, likely due to external factors, such as the COVID-19 pandemic. There is also a stabilization trend between 2017 and 2022, indicating that the technological field is in the maturation phase, and no longer in an emerging stage.

Therefore, the analysis of the temporal evolution of patent families reveals an initial peak of publications in 2016, followed by consistent levels of innovative activity until 2022. The drop observed in 2020 can be attributed to global cyclical factors, such as the COVID-19 pandemic. However, the data indicate recovery in subsequent years (2021-2022), evidencing the resilience of the innovation system. The sharp reduction in recent years reflects, above all, limitations inherent to the time of publication of patent documents, generating a time lag in the availability of data - a typical limitation of patentometric analyses. Taken together, the results indicate that technologies related to geological hydrogen are in a consolidation stage, maintaining continued relevance in the context of the energy transition.

LEGAL SITUATION

The legal situation allows us to assess the degree of maturity, effective protection, and life cycle dynamics of technologies related to geological hydrogen. It is an essential indicator to understand the technological strength, economic attractiveness, and stage of development of the field, as can be seen in Figure 4.

Figure 4 – Legal situation



Source: Authorship (2026)

The granted patents (180 documents) represent technologies that have undergone technical examination and met the requirements of novelty, inventive step and industrial application, indicating a high degree of technological consolidation.

Figure 4 shows that most inventions are already formally protected, demonstrating that the field is not only emerging, but already has mature and validated solutions, which suggests strong commercial and industrial interest.

The pending patents (74 documents) correspond to the applications still under analysis by the patent offices, evidencing the continuity of the innovative effort and indicating that the field remains in active expansion. This set also represents the future technology pipeline.

Abandoned patents (36 documents) refer to processes interrupted by applicants, whose possible causes include low economic viability; strategic changes; technical failure or high maintenance costs. These conditions reflect technological risks and uncertainties associated with part of the solutions developed.

Terminated (12 documents) and expired (12 documents) patents indicate the termination of protection, either voluntarily or due to default. In these cases, the technologies may have lost relevance, been superseded, or become public domain, opening up opportunities for free use and incremental innovation.

Patents without information on the legal situation (6 documents) correspond to those in which the patent office has not provided updated data. Even so, it is assumed that they are, for the most part, in the concession or analysis phases.

The withdrawn patents (2 documents) indicate that the applicants abandoned the granting process. This decision may be associated with changes in strategic focus, redirection of the technological portfolio, redefinition of R&D priorities, identification of anteriority, or technical, legal, and economic factors.

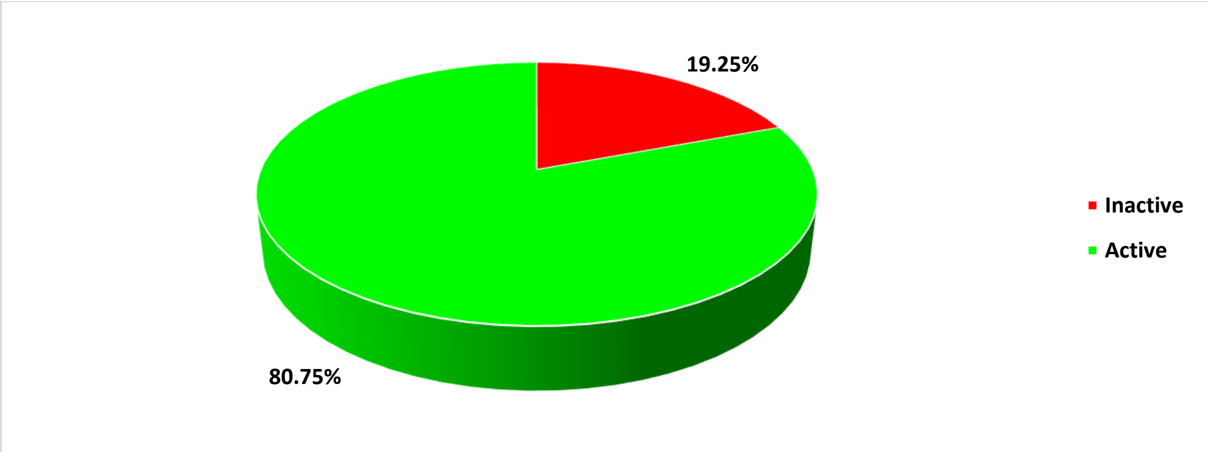
The high proportion of patents granted demonstrates that the sector has already gone beyond the initial phase, presenting validated and applicable technologies. The significant volume of pending orders reinforces the continuity of investments and the constant evolution of technological solutions. On the other hand, the presence of abandoned and expired patents evidences the natural process of technological selection, in which not all solutions achieve viability. In addition, expired or terminated patents represent an opportunity for technology transfer, open innovation and exploitation without legal restrictions.

Therefore, the analysis of the legal situation of patents reveals a technological field at an advanced stage of consolidation, evidenced by the predominance of granted documents. At the same time, the significant presence of pending applications indicates the continuity of innovative dynamism, suggesting that technologies related to geological hydrogen remain evolving. The occurrence of abandoned and expired patents reflects the process of technological selection, in which only solutions with technical and economic feasibility are maintained. Together, these results point to a strategic sector, with a high degree of maturity, but still open to new opportunities for technological development and exploration.

LEGAL STATUS

The legal status synthesizes, in aggregate form, whether patents are still in force (active) or have already lost legal effect (non-active). This indicator is crucial to assess the level of effective protection, technological competitiveness, and opportunities for exploitation, as can be seen in Figure 5.

Figure 5 – Legal status



Source: Authorship (2026)

Figure 5 demonstrates the predominance of active patents (260 documents), indicating that they remain valid and under current legal protection. These patents may be granted and in force or under analysis (pending). This scenario highlights a strong strategic and economic interest in the field of technological hydrogen, demonstrating that aaplicants continue to bear the maintenance costs and preserve technological exclusivity. Such behavior suggests a highly competitive environment and the existence of barriers to entry, characterizing a highly protected and expanding technological field.

Non-active patents (62 documents) include those that have expired, abandoned, ceased, and been withdrawn. These documents represent technologies that have lost strategic value, have not presented economic viability, or have already entered the public domain. In this context, such technologies can be reused, adapted or serve as a basis for incremental innovation processes.

The high percentage of active patents indicates a sector still in a dynamic phase of exploration and investments, with strong retention of intellectual property rights. This scenario characterizes a competitive and relatively closed market, in which many technologies remain protected, reducing freedom to operate. On the other hand, non-active patents make room for open innovation, creating opportunities for startups, universities, and emerging countries. This pattern is also consistent with the context of the energy transition, reflecting the global growth of hydrogen as an energy vector and its relevance in decarbonization and energy security strategies.

Therefore, the analysis of the legal status of patents shows the predominance of active documents, indicating a high degree of technological protection and continued strategic interest in the development of solutions related to geological hydrogen. This scenario reflects a competitive environment, in which innovative agents seek to ensure exclusivity and market positioning. On the other hand, the presence of non-active patents reveals opportunities for technological exploration and incremental innovation, contributing to the dissemination of knowledge and to the expansion of development possibilities in the sector.

LIFE CYCLE OF PATENTS

The patent life cycle considers three main dimensions: priority (initial filing), publication, and legal status. Its interpretation can be structured in four fundamental points:

Temporal dynamics of the patenting process

The priority dates are mainly concentrated between 2014 and 2021, indicating the period of greatest inventive activity. Publication dates generally occur one to two years after filing, which is consistent with the patent system's standard term, usually 18 months.

The time flow is aligned with the expected functioning of patent offices, evidencing a continuous pipeline of innovation over the years.

Predominance of patents granted

There is a strong presence of the "granted" status throughout the entire series, which indicates a high success rate of orders. This result suggests that the deposits have good technical and legal quality, meeting the criteria of novelty, inventive step and industrial application. In addition, it can reflect the performance of large companies and institutions with consolidated experience in intellectual property.

Significant presence of discontinuity (dropout, expiration, and cessation)

In addition to those granted, the status of abandoned, expired (related to fees), terminated and withdrawn often stands out. These statuses reveal important aspects:

- Abandonment/withdrawal: strategic decisions associated with market changes, economic unfeasibility or technological limitations;
- Expiration by fees: indicates difficulties in maintaining the asset, suggesting low commercial viability in certain cases;
- Termination: possible loss of rights resulting from the absence of operation or maintenance.

These conditions show that not all technologies reach the stage of economic exploitation,

Recent growth in pending orders

From the period between 2019 and 2026, there is a significant increase in the number of patents with pending status or without updated data from legal events. This behavior reflects the natural time of examination of applications (patent office backlog), indicating that the latest technologies are still in the evaluation phase. Such a trend suggests continuity and expansion of innovative activity in the technological domain analyzed.

Technological maturity of the field

Based on the dataset, it is possible to identify three distinct phases:

- Initial period (2014-2016): high proportion of patents granted, indicating technologies already consolidated.
- Intermediate period (2017-2019): coexistence of concessions and discontinuities, characterizing a phase of technological adjustment and selection.
- Recent period (2020-2023): predominance of pending applications, indicating an expanding technological frontier.

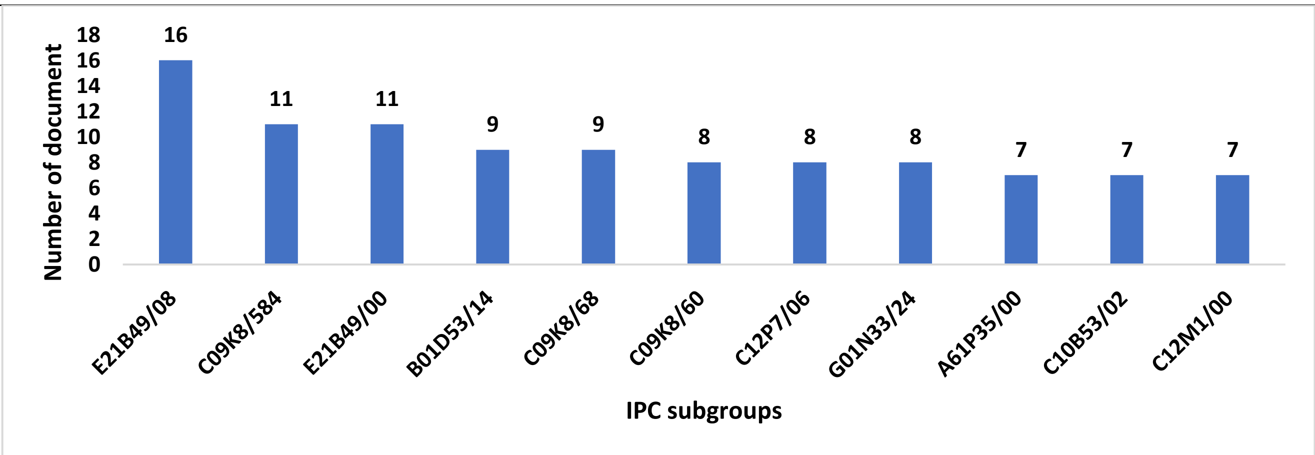
Thus, the technological field presents a level of maturity between intermediate and advanced, combining technologies already consolidated (granted) with new emerging trajectories still under analysis.

Therefore, the data show a dynamic innovation system, characterized by a continuous flow of deposits, a high concession rate and the relevant presence of technological discontinuity. The coexistence of granted patents and pending applications indicates a technological field in constant evolution, with maturity consolidated in previous periods and recent expansion that drives new opportunities for development and economic exploration.

IPC SUBGROUP

The IPC subgroup reveals the detailed technological structure of patents related to technological hydrogen, allowing the identification of dominant areas, technological convergence and emerging applications. In view of the high number of subclasses, the analysis was structured by means of technological nuclei (clusters), as can be seen in Figure 6.

Figure 6 – IPC Subgroup



Legend

E21B49/08: Tests to determine the nature of borehole walls; Training rehearsals; Methods or apparatus for sampling soil or well fluids, specially adapted for drilling in soil or wells; / Obtaining samples of the fluid or test fluids, in boreholes or wells;

C09K8/584: Compositions for drilling holes or wells; Compositions for the treatment of holes or wells, e.g. for finishing or repairing operations; / Compositions for optimization methods in the recovery of hydrocarbons, i.e. to improve oil mobility, e.g. displacement fluids; / characterized by the use of specific surfactants;

E21B49/00: Tests to determine the nature of borehole walls; Training rehearsals; Methods or apparatus for sampling soil or well fluids, specially adapted for drilling in soil or wells;

B01D53/14: Separation of gases or vapours; Recovery of volatile solvent vapours from gases; Chemical or biological purification of exhaust gases, e.g. engine exhaust gases, fumes, fumes or exhaust gases, aerosols; / by absorption;

C09K8/68: Compositions for drilling holes or wells; Compositions for the treatment of holes or wells, e.g. for finishing or repairing operations; / Compositions to stimulate production by acting on the underground formation; / Compositions to form cracks or fractures; / Compositions based on water or polar solvents; / containing organic compounds;

C06K8/60: Production of compounds (including biohydrogen);

C12P7/06: Preparation of oxygen-containing organic compounds; / containing a hydroxyl group; / acyclic; / Ethanol, i.e. not for drinking;

G01N33/24: Investigation or analysis of materials by specific methods not covered by the groups; / of earth materials;

A61P35/00: Antineoplastic agents;

C10B53/02: Destructive distillation, specially adapted to certain solid raw materials or specially-shaped solid raw materials; / of material containing cellulose;

C12M1/00: Apparatus for enzymology or microbiology.

Source: Authorship (2026)

Figure 6 shows the main technological trends and application areas, which can be grouped into the following clusters:

Dominant core: oil, gas and geosciences (E21B/C09K)

The main codes identified are: E21B49/08 (well measurement and monitoring), E21B49/00 (well investigation), E21B43/xx (recovery of fluids, such as oil, gas and hydrogen) and C09K8/584, C09K8/68, and C09K8/60 (drilling fluids and chemical compositions). This set constitutes the central core of the technology, indicating a strong concentration in activities of geological exploration, drilling, injection and extraction of gases, including hydrogen. Such evidence reinforces that geological hydrogen is strongly anchored in the infrastructure and know-how of the oil and gas industry.

Chemical Processes & Gas Separation (B01D / C01B / C25B)

Codes B01D53/14 (gas separation), C01B3/38 and C01B3/48 (hydrogen production – 5 documents each), C25B1/04 (electrolysis), and C25B15/08 (electrochemical cells – 5 documents) stand out. These results indicate a strong presence of technologies aimed at the production, purification, and separation of hydrogen, as well as electrochemical processes. Therefore, the integration between geological hydrogen (natural or stored) and industrially produced hydrogen is observed, evidencing convergence between chemical engineering and energy.

Biotechnology and biological production (C12P/C12N/C12M)

The main codes include C12P7/06 (production of compounds, including hydrogen), C12N1/20 (microorganisms – 6 documents), and C12M1/00 (biotechnological equipment). The presence of these codes indicates the development of biological routes for the production of hydrogen and the use of microorganisms in energy processes, configuring an emerging and sustainable strand, in which hydrogen is not only of geological origin, but also bioenergetic.

Monitoring, Sensing, and Geophysics (G01N/G01V/G01R)

Codes G01N33/24 (materials analysis), G01N24/08 (magnetic resonance imaging / structural analysis – 6 documents), and G01V3/32 (geophysical prospecting – 5 documents), stand out. These results indicate the development of technologies aimed at the detection of hydrogen in reservoirs, analysis of rocks and fluids, and underground monitoring, which are essential to ensure the feasibility and safety of geological storage.

Fossil fuel processing and energy transition (C10G / C10B / C10L)

Key codes include C10B53/02 (coal/biomass processing), C10G1/00 (petroleum refining – 6 documents), and C10L5/36 (fuels – 4 documents). These results demonstrate the integration between traditional technologies, such as oil and coal, and new hydrogen production routes, indicating a process of gradual transition, rather than immediate replacement. Hydrogen, in this context, is incorporated into the existing fossil chain.

Medical & Pharmaceutical (A61K/A61P)

The most relevant codes are A61P35/00 (therapeutic use, such as in cancer treatment), A61K31/7088 (chemical compounds – 6 documents), and A61K39/395 (immunological preparations – 6 documents). These data indicate emerging applications of hydrogen in the health area, especially in therapies, use as an antioxidant and biomedical applications, evidencing technological diversification beyond the energy sector.

Environmental Technologies (C02F / C04B / C08J)

Codes C02F1/68 (water treatment – 4 documents), C04B28/00 (construction materials – 4 documents), and C08J9/00 (porous materials – 4 documents) stand out. These results indicate applications of hydrogen in industrial processes, development of sustainable materials and energy infrastructure, reinforcing its role in the environmental agenda.

High technological dispersion (long tail)

The presence of numerous codes with low frequency (one or two documents) is observed, indicating strong interdisciplinarity and expansion to emerging applications in areas such as agriculture, food, advanced materials, and artificial intelligence.

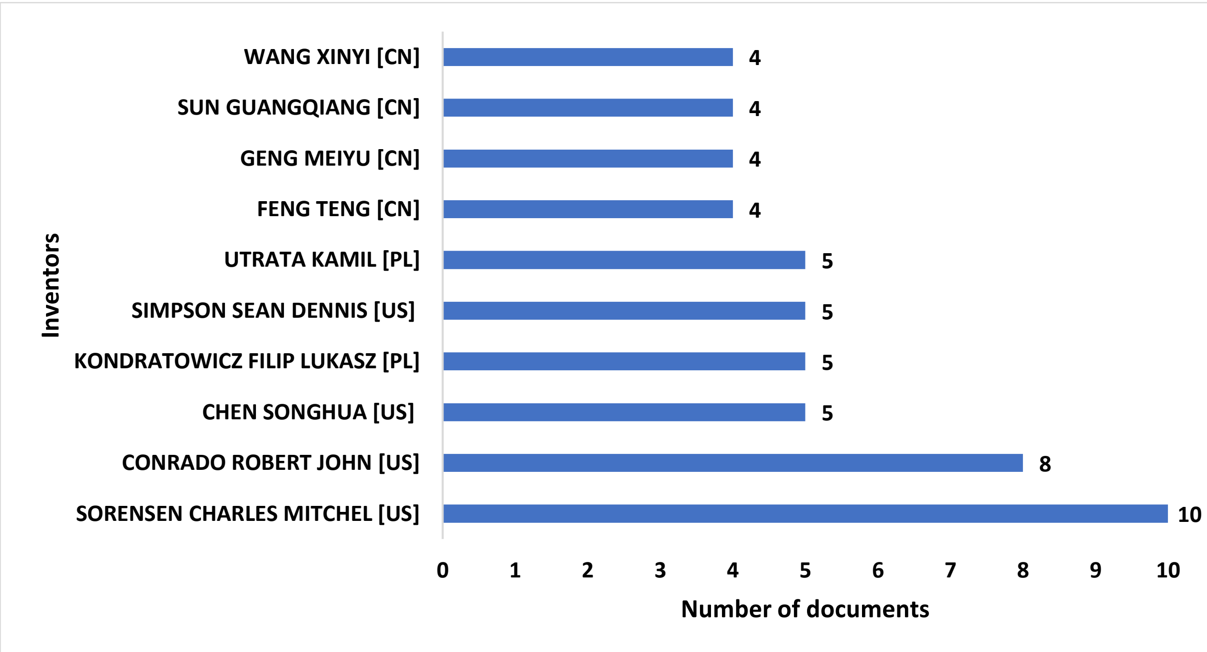
In general, the predominance of the oil and gas sector is verified, showing that the technological basis of geological hydrogen is still anchored in reservoir engineering. However, there is a strong technological convergence, with integration between geology, chemistry, biotechnology, and energy engineering. In addition, the emergence of sustainable routes, such as biohydrogen, electrolysis, and environmental technologies, as well as the diversification of applications for areas such as health, materials, and the environment, stands out.

Therefore, the distribution of the IPC subgroups shows that technologies related to geological hydrogen have a strong concentration in the areas of oil and gas engineering, especially in drilling, monitoring and fluid recovery activities. At the same time, there is a growing convergence with chemical, electrochemical, and biotechnological processes, indicating the diversification of hydrogen production and application routes. The presence of subclasses associated with geophysical monitoring and material analysis reinforces the importance of control and safety in underground reservoirs. In addition, the technological dispersion identified suggests a highly interdisciplinary field, in the process of expanding to sectors such as health, environment, and advanced materials, characterizing hydrogen as a strategic vector in the energy transition.

INVENTORS

The analysis of inventors reveals relevant patterns about the structure of knowledge generation and the dynamics of innovation in the set of patents analyzed. The main inventors can be seen in Figure 7.

Figure 7 – Main inventors



Source: Authorship (2026)

Figure 7 shows that, among the ten most relevant inventors, American and Polish inventors stand out at the top. The Polish presence is mainly associated with the performance of the Synthos company.

The interpretation can be organized into three levels: concentration, technological leadership, and dispersion of knowledge.

There is a relative concentration in a few inventors, but without absolute dominance. The inventor with the most documents is Charles Mitchel Sorensen, followed by Robert John Conrado and a group of four inventors with five documents each. This pattern indicates the existence of technological leaders, but without a significant monopoly on inventive activity. Such a configuration suggests a competitive and collaborative technological field, in which different specialists contribute in a relatively balanced way.

There is a strong predominance of American inventors among the most productive. Most of the inventors with the highest number of patents are linked to the USA, reinforcing its role as the main pole for the generation of technological knowledge in this domain. In addition, there is relevant participation of Polish, Chinese, Belgian, French, and British inventors, evidencing an internationalized and multicentric innovation environment.

The presence of 39 recurrent inventors is also identified, with three to five documents, indicating the existence of consolidated research teams or robust institutional links, such as companies, universities, and R&D centers.

On the other hand, approximately 947 inventors are associated with one or two documents, which demonstrates a high dispersion of inventive activity - a typical characteristic of dynamic and expanding technological areas. This pattern suggests the continuous entry of new actors in the field, the diversity of technological applications, the relatively low barrier to entry for innovation, and the presence of collaborative networks.

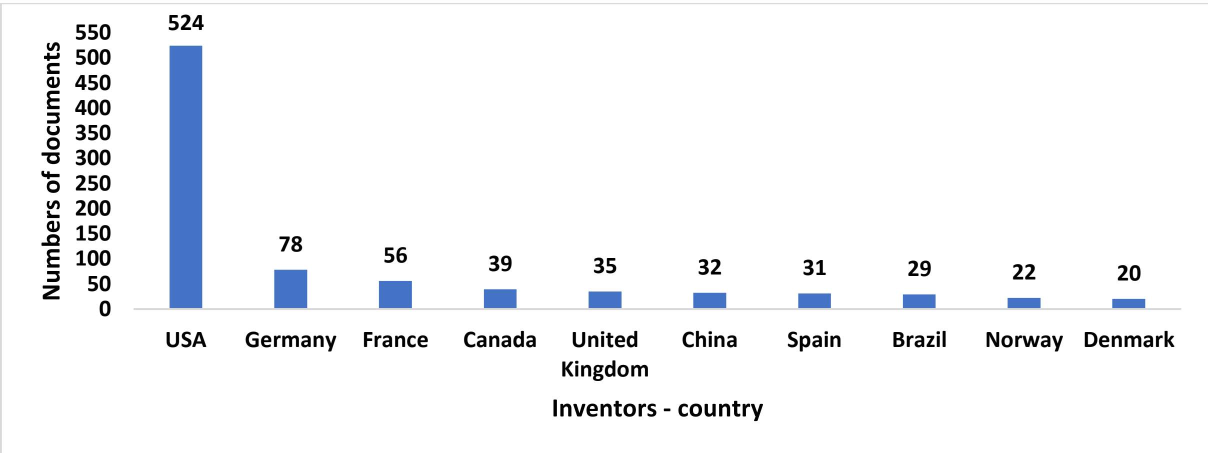
There is also a reduced participation of Brazilian inventors, generally linked to national companies, which shows the limited local generation of technology related to geological hydrogen, despite the relevance of Brazil as a protection territory and a major oil producer.

Therefore, the results indicate that the inventive activity has a partially concentrated structure, but widely distributed, with significant leadership of American inventors and expressive participation of multiple countries. The coexistence of highly productive inventors with a broad base of occasional inventors suggests an open, competitive, and globalized innovation ecosystem, in which both large players and new entrants contribute to technological advancement.

COUNTRY OF INVENTORS

The country of the inventors reveals the geographical origin of the innovative capacity in technologies related to geological hydrogen, demonstrating which nations effectively develop technological knowledge, as can be seen in Figure 8.

Figure 8 – Country of Inventors



Source: Authorship (2026)

The global leadership is from the USA, the country that concentrates the greatest inventive capacity, indicating strong investment in R&D, leadership in the energy and technological sectors and the presence of large companies and research centers, configuring itself as the main center for the generation of knowledge on the subject. This pattern is consistent with international studies that point to the US as the top leader in hydrogen patents, alongside countries such as Japan and members of the European Union [43].

There is a significant European presence, with emphasis on Germany, France, the United Kingdom, Spain, Norway, and Denmark. These countries make up a robust and distributed innovative ecosystem, with a strong presence in energy transition, environmental technologies, and geological storage. Europe is thus consolidated as the second main technological hub, characterized by high regional cooperation and scientific integration.

The Asian participation is also relevant, especially with the presence of China, Japan, India (5 inventors), and Israel (3 inventors). Although the continent has a consistent performance, its dominance is still lower than that observed in other technological sectors, indicating a field in the process of consolidation, but with high potential for future expansion. Recent studies even indicate a growing global diffusion of hydrogen technologies, with initial concentration in a few countries and subsequent international expansion [44].

In the American continent, excluding the USA, Canada, Brazil, Chile (2 inventors), Mexico (1 inventor), and Venezuela (1 inventor) stand out. Canada has a significant share, possibly associated with the availability of natural resources and favorable geological conditions. Brazil stands out in a relative manner, showing relevant inventive capacity, although lower than that of the main leading countries.

About 18 countries have low participation, with one to ten inventors, which indicates punctual or specialized contributions, possibly associated with technological niches or participation in international collaborative networks.

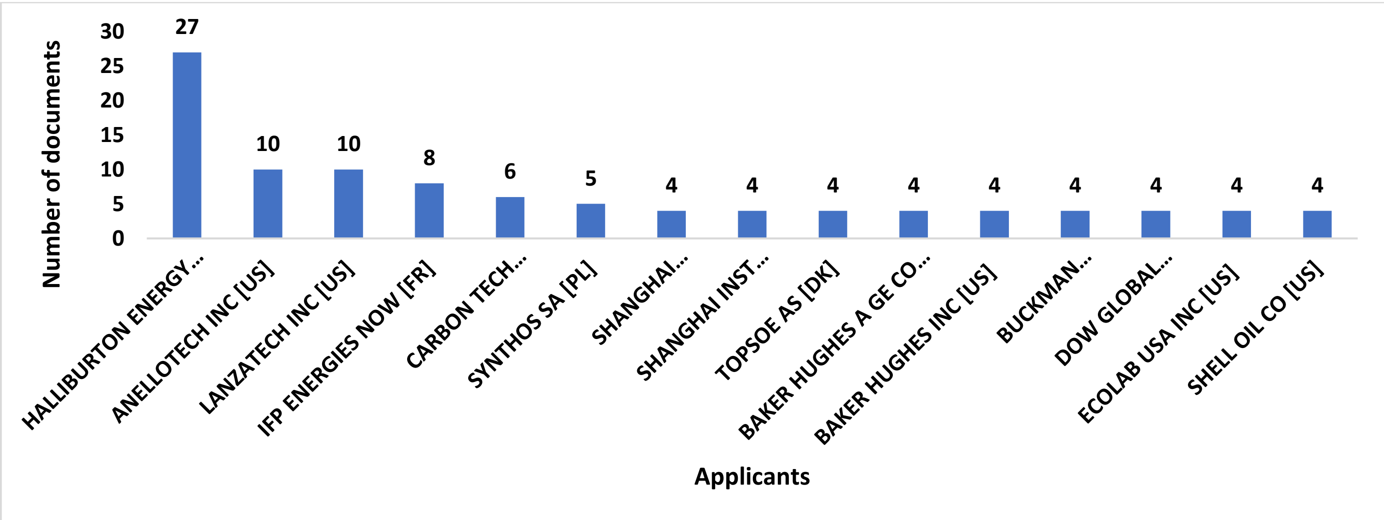
Figure 8 shows that the centralization of knowledge remains in the US, while Europe acts as a complementary hub, underpinned by the diversity of innovative countries and strong scientific and industrial base. Brazil, in turn, is a leader as a protection territory, but not as the main generator of technology, characterizing itself more as a strategic target market than as an innovative core. Still, emerging countries such as Brazil, China, and India have significant growth potential in R&D and applied innovation.

Therefore, the analysis of the inventors' country of origin shows a strong concentration of inventive capacity in the USA, which stands out widely as the main pole for the generation of technological knowledge in the field of geological hydrogen. Europe has a robust and distributed innovative ecosystem, while Asian countries demonstrate relevant participation, but still in consolidation. In the Latin American context, Brazil emerges as an important player, although its inventive contribution is still inferior to that of the leading countries. The comparison between the origin of inventors and countries of protection reveals a mismatch between the generation of knowledge and markets of interest, indicating that certain regions, such as Brazil, are strategic for economic exploration, but still lack greater prominence in the generation of innovation.

APPLICANTS

Ownership by number of documents reveals the structure of corporate and institutional concentration of technological property, allowing the identification of the main actors that dominate the field analyzed, as can be seen in Figure 9.

Figure 9 – Main applicants



Source: Authorship (2026)

Figure 9 shows the predominance of U.S. companies in the scenario of the patents analyzed. It is observed that approximately two-thirds (2/3) of the most relevant ownership properties belong to this country, confirming its leadership in R&D focused on the exploration, storage, and geological use of hydrogen.

There is a high concentration in large corporations, especially the company Halliburton Energy Services Inc, which presents 27 documents, placing itself far ahead of the others. This result indicates strong technological leadership in the sector, high investment capacity in R&D and strategic performance in the protection of innovations.

Next, the American companies Anellotech Inc (10 documents) and Lanza Tech Inc (10 documents), and the French IFP Energies Now (8 documents) stand out. These organizations make up the dominant core of innovation, accounting for a significant portion of patents.

There is also the presence of state-owned companies and multinationals in the energy, chemical, and biotechnology sectors, such as PETROBRAS, Halliburton, Baker Hughes, Shell, BP, and ExxonMobil (energy and oil); Dow, BASF, Arkema, and Clariant (chemistry and materials); and Novartis, CureVac, Shanghai Green Valley (biotechnology and health). This scenario indicates that the technological field analyzed is strongly associated with the energy transition, advanced chemical processes, and sustainable and industrial solutions.

After the main leaders, an intermediate group composed of 27 organizations with three to six documents is identified, including companies such as PETROBRAS, Carbon Tech Holdings, Synthos, and Schlumberger.

In addition, there are a large number of holders with one or two documents - about 198 - characterizing a "long tail" of innovation. This pattern suggests the presence of startups, universities, and research centers, in addition to the continuous entry of new players in the technological market and the diversity of applications and niches.

Most applicants are from USA, reinforcing the country's global leadership in intellectual property, as well as the strong integration between companies, universities, and the market, and the ability to transform research into technological assets. European countries, such as Germany, the United Kingdom, France, and Switzerland, also have a relevant participation, although on a smaller scale.

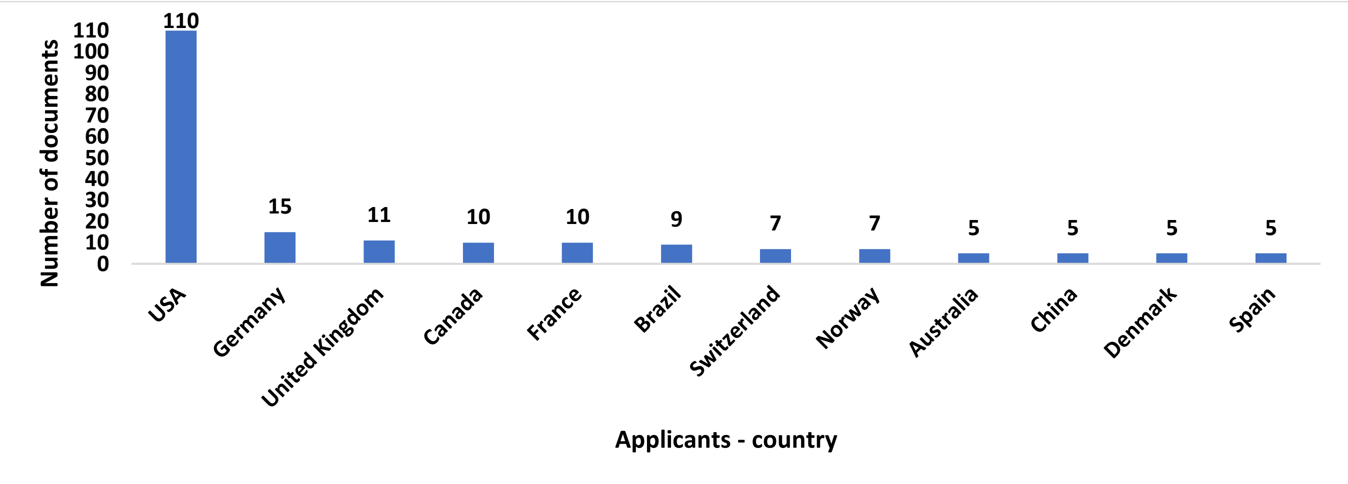
Although Brazil is listed as a territory for the protection of these patents, it is not the origin of the majorit of them. Brazilian participation is still limited, but strategic, with some relevant applicants, such as PETROBRAS and the State University of Campinas (UNICAMP), in addition to other institutions with reduced participation. This scenario indicates an important institutional presence, especially of universities and state-owned companies, as well as potential for innovation, although with low insertion on an international scale.

Therefore, the ownership structure reveals a highly concentrated system dominated by large multinational corporations, especially U.S., especially companies in the energy and chemical sectors. An oligopolized pattern is observed, in which a few actors concentrate a large part of the patents, coexisting with a broad base of occasional participants. This scenario shows that the dynamics of innovation is simultaneously centralized in the major players and dispersed among new entrants and research institutions, reflecting a competitive, globalized, and knowledge-intensive technological environment.

COUNTRY OF APPLICANTS

The country of the holders (patent applicants) shows the geographical distribution of intellectual property control, offering relevant insights into the concentration of technological power and global leadership, as can be seen in Figure 10.

Figure 10 – Main countries of applicants



Source: Authorship (2026)

Figure 10 demonstrates a very strong concentration in the USA, with 110 applicants, a number significantly higher than in the other countries. This result indicates that the country plays a dominant role not only in invention, but, above all, in the ownership and economic appropriation of technologies, which reinforces its position as the main global center for innovation and protection of intangible assets.

At a second level, there is a group of countries with intermediate participation, especially Germany, the United Kingdom, Canada, and France. These countries are important technological hubs, generally associated with industrialized economies and robust national innovation systems, with a strong presence of multinational companies, universities, and research centers.

With moderate participation, there are Brazil, Switzerland, Norway, Australia, China, Denmark, and Spain. The case of Brazil is particularly relevant, as it indicates a still limited but significant presence in the global scenario of technological ownership, suggesting the capacity to generate and protect innovations, even if far from the main leaders.

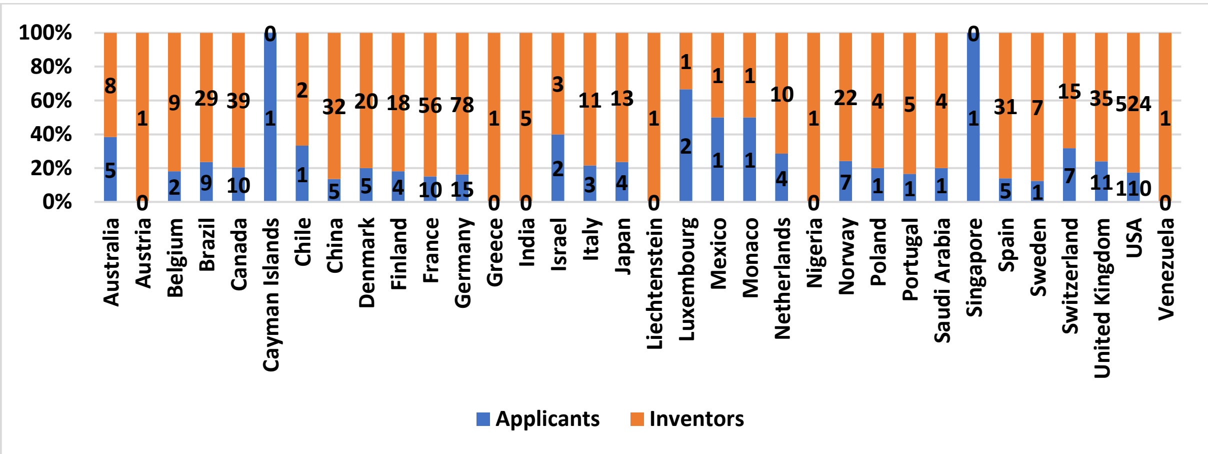
In addition, there are 16 countries with low participation, ranging from one to four applicants, such as Finland, Japan, the Netherlands, among others. This dispersion indicates peripheral or specialized participation in technological niches, possible action in national or international cooperation, and less capacity to internalize intellectual property.

Therefore, the distribution of applicants reveals a highly concentrated and asymmetrical structure, with clear USA hegemony in the appropriation of intellectual property. European countries and Canada form a relevant secondary bloc, while emerging economies, such as Brazil, still have an incipient participation. This pattern suggests that, although inventive activity is globally distributed, economic and legal control of technologies remains concentrated in a few countries, reflecting structural inequalities in national innovation systems and in the ability to protect technological assets.

COUNTRY APPLICANTS X COUNTRY INVENTORS

The relationship between the country of applicants and the country of the inventors allows for a more sophisticated analysis of the geography of innovation, distinguishing between who generates knowledge (inventors) and who owns the intellectual property (applicants), as can be seen in Figure 11.

Figure 11 – Country of inventors vs. country of applicants



Source: Authorship (2026)

The USA has 110 applicants and 524 inventors, consolidating an absolute leadership in both dimensions. This result indicates a strong internal capacity for knowledge generation, high retention of intellectual property and a highly structured and integrated innovation system, that is, the country not only innovates, but also economically appropriates these innovations.

A certain balance is observed in some countries that manage to simultaneously innovate and retain intellectual property, presenting relative equivalence between inventors and applicants. Germany (15 applicantsders and 78 inventors), France (10 applicants and 56 inventors), the United Kingdom (11 applicants and 35 inventors) and Canada (10 applicants and 39 inventors) stand out. These countries configure mature innovation systems, in which there is a high capacity for scientific and technological production, as well as efficiency in the conversion of this knowledge into protected assets.

On the other hand, some countries show high knowledge generation but lower economic appropriation. This group has a higher number of inventors compared to applicants, indicating possible technological dependence or transfer of intellectual property to external actors. China (5 applicants/32 inventors), Spain (5/31), Brazil (9/29), and Belgium (2/9) stand out. This pattern suggests that part of the inventions may be being registered by foreign companies, evidencing insertion in global innovation chains, but with less control over economic results.

In the case of Brazil, this scenario reveals a system under development, with relevant inventive capacity, but with limitations in the internalization of intellectual property, which reduces the economic use of the innovations generated.

Some countries exhibit peripheral or highly specialized participation, with few applicants and inventors, or only inventors, such as India (0 applicant / 5 inventors), Venezuela (0/1), Nigeria (0/1), Liechtenstein (0/1), Greece (0/1), and Austria (0/1). This condition indicates punctual participation, usually associated with international collaborations, performance in specific niches, and less technological protection infrastructure.

There are also atypical cases where there is an applicant, but there are no inventors registered in the corresponding country, such as the Cayman Islands (1 applicant / 0 inventors) and Singapore (1/0). This pattern may reflect tax or legal strategies, with the use of holding companies, subsidiaries, or jurisdictions favorable to the protection of intellectual property.

Therefore, the data show a structural asymmetry between the generation and appropriation of knowledge, with a strong concentration in the USA and, to a lesser extent, in developed European countries. While some nations have balanced innovation systems, others – especially emerging economies – demonstrate relevant inventive capacity, but with low retention of ownership, indicating subordinate insertion in global innovation chains. This scenario reinforces the need for public policies aimed at strengthening the protection of intellectual property, technology transfer, and the internalization of innovation results, especially in countries like Brazil.

FINAL CONSIDERATIONS

The present study allowed us to comprehensively map the technological panorama related to geological hydrogen from a patentometric analysis, evidencing relevant patterns of temporal evolution, geographic distribution, ownership structure, inventors' profile, and intellectual property dynamics. The results indicate that it is a technological field in the process of consolidation, with a consistent development trajectory between 2016 and 2022, followed by an apparent recent retraction that, in reality, reflects limitations inherent to the period of patent secrecy.

The analysis revealed a strong concentration of innovative activity and ownership in the United States of America (USA), which stands out as the main global hub in both the generation and appropriation of knowledge. European countries are a relevant and complementary technological bloc, characterized by mature innovation systems and a high capacity to convert knowledge into protected assets. On the other hand, emerging economies, such as Brazil, although they have a significant participation as protection markets and with growing inventive capacity, still face challenges in the internalization of intellectual property and in the consolidation of an innovative ecosystem competitive on a global scale.

From a technological point of view, there was a strong predominance of applications associated with the oil and gas industry, especially in fluid exploration, monitoring, and recovery activities, showing that geological hydrogen is strongly anchored in the infrastructure and pre-existing knowledge of this sector. At the same time, a growing convergence with areas such as chemical processes, electrochemistry, biotechnology and environmental technologies was identified, indicating diversification of technological routes and reinforcing the role of hydrogen as a strategic vector in the energy transition.

The ownership structure demonstrated an oligopolized pattern, with a predominance of large multinational corporations, coexisting with a broad base of secondary actors, such as universities, startups, and research centers. This configuration reflects an innovation environment that is simultaneously concentrated and dynamic, in which there is room for both major players and new entrants.

In addition, the analysis of the relationship between the country of the inventors and applicants showed a relevant asymmetry between generation and appropriation of knowledge, suggesting that a significant part of the innovations developed in certain countries is economically captured by external actors. This scenario reinforces the importance of public policies aimed at strengthening national innovation systems, protecting intellectual property, and promoting technology transfer.

As contributions, the study offers relevant subsidies for the formulation of business strategies and public policies, by identifying technological trends, key actors, and structural gaps in the field of geological hydrogen. However, it has limitations inherent to the very nature of patent data, such as the time lag of publication and the possibility of underrepresentation of non-patented innovations.

As a future agenda, it is recommended to deepen the analysis through integration with scientific data (articles), studies of collaboration networks, evaluation of the economic impact of technologies, and investigation of public policies aimed at the development of hydrogen in different countries. It is also suggested that the scope be broadened to include international comparisons and prospective analyses, aiming to understand the role of geological hydrogen in the broader context of the global energy transition.

In summary, the results confirm that geological hydrogen represents a strategic technological field, with high potential to contribute to energy security and decarbonization, although marked by structural asymmetries in the global distribution of innovation and intellectual property.

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