Hydrogen TCP

Task 49 Natural Hydrogen

Subtask C

TASK 49- REPORT

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SUBTASK C E&P ACTIVITY WORLWIDE

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Key messages

- H_2 Exploration activity started in all continents, except Antarctica, within the countries where it is already legal
- However, by mid-2025, the only production of natural H_2 remains the Bourakébougou field in Mali.
- In 2025 the more advanced countries are Australia and US
- The activity is driven by start-ups but large organizations, such as the National Oil Companies and mining companies are starting to evaluate their asset H_2 potential

Abstract

Exploration for natural H_2 has begun in all countries where it is permitted by subsurface law, but these remain a small minority worldwide. While the rocks that generate H_2 are becoming fairly well known, it is not yet possible to define the optimal geological conditions for economical H_2 production due to a lack of well data. The number of wells drilled is still limited due to the slow pace of change in mining law and, in some countries, the slow pace of work permits, but also because many operators are small companies that need to raise funds to operate. The first exploratory drilling has already taken place in Mali, Australia, the USA and Canada. Many of the wells have shown, with H_2 content sometimes over 80%, and the delineation of reserves and estimation of their economic viability are now underway. Licenses can be obtained in around ten countries, including France, where five companies are already operating. The arrival of large companies, national companies (such as for South America Petrobras or Ecopetrol), but also certain major international companies, particularly mining companies, could accelerate things. In natural resources, usually the production starts ten years after the start of the exploration, early to mid 2030's seems realistic for the beginning of the production.

Introduction

Considerable uncertainty surrounds nascent "Hydrogen systems", particularly on the existence of economic reserves; however, exploration is now underway in pursuit of what may emerge as the cheapest and lowest carbon source of hydrogen [1]. Exploration activities to date have been localized to countries where legislation is mature and significant scope remains in a number of locations with favorable geological settings.

Globally, there are several possible approaches to estimate the world's high-potential zones, either based on indices, as done by [2] and resulting in the well-known map of the area with H_2 over 10% as free gas or dissolved (Fig. 1), or based on the presence of potential generating rocks, as done by [3] (Fig. 2). The latter authors propose a synthetic approach by grouping reaction/rock pairs. They defined four types of H_2 generating rock (GR) for mapping purposes. In detail, numerous redox reactions can generate H_2, but the geological contexts less so. GR_1 corresponds to oceanic or mantle rocks, it represents a small surface of the earth, whereas the GR_2 that corresponds to sedimentary and intrusive rocks rich in iron are present in many cratons. GR_3 corresponds to radiolysis, and GR_4 to the late maturation of organic matter (OM), particularly coal.

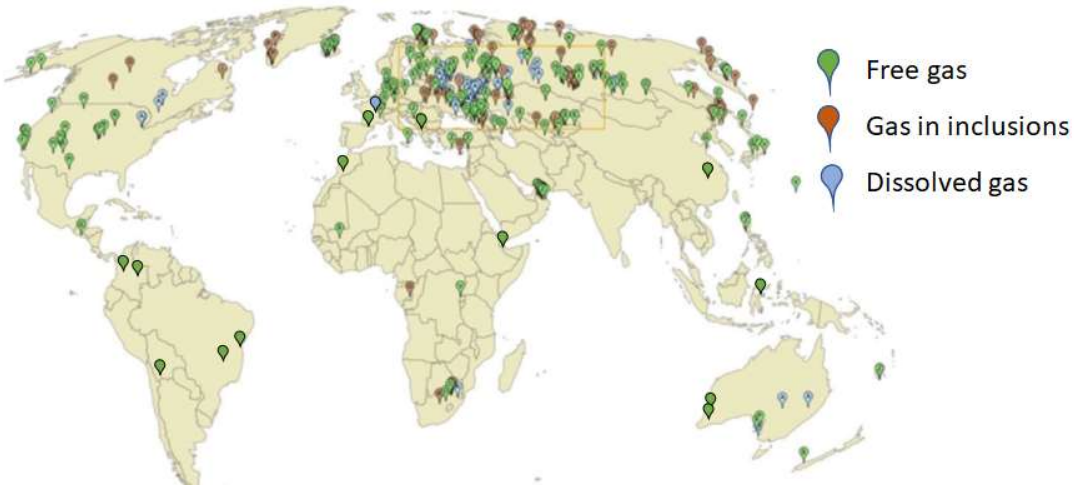

FIGURE 1: SOME KNOWN OCCURRENCE OF NATURAL HYDROGEN, H2 CONTENT ABOVE 10% OF VOLUME, MODIFIED FROM [4] WITH ADDITIONAL POINTS IN SOUTH AMERICA, MOROCCO, CHINA, FRANCE AND AUSTRALIA.

The initial map of natural H_2 occurrences worldwide (Fig. 1) was highly dependent on data availability and the initial map [4] has a strong focus on North America, Russia, and Ukraine, but in 2020 was blank for large areas such as South America [4]. More recent data have been now added. Combining the different approaches and datasets provides a more global view.

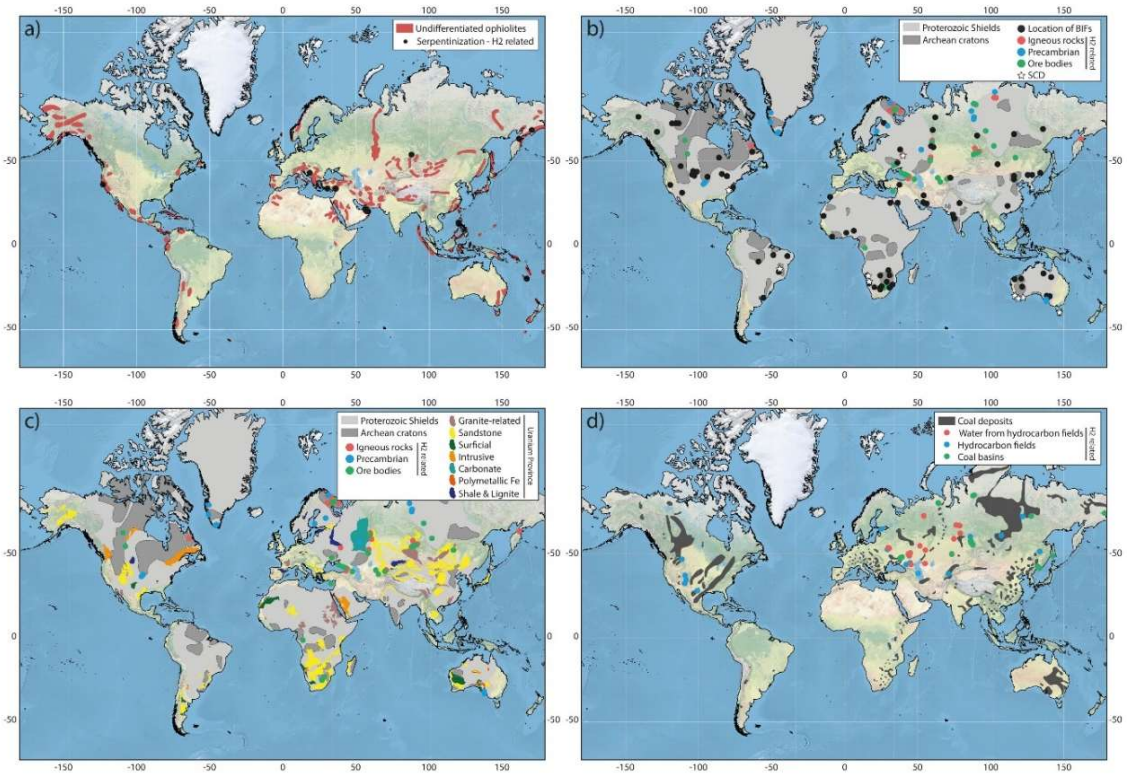

FIGURE 2: WORLD MAPS SHOWING THE MAIN POTENTIAL SOURCE ROCKS ASSOCIATED WITH THE REACTION TYPE (A) SERPENTINIZATION, (B) OXIDO-REDUCTION OF SEDIMENTARY AND

INTRUSIVE ROCKS, (C) RADIOLYSIS, (D) COAL BASINS/LATE MATURATION OF ORGANIC-RICH ROCK). EXTRACTED/MODIFIED FROM [3].

In this synthesis, we describe by continent in the following sub-chapters what is already known, while being very aware that data is being acquired on a daily basis, and that some of it is not being shared, as competition in the mining sector is now fierce. Countries are classified in 3 groups, (1) where the production is established, namely the Mali, (2) where the exploration is active, i.e. the regulatory framework allows to ask for exploration licences as in South Australia, US or France and (3) where some data are available usually thanks to academic research groups. In grey the countries where activity is low or unknown.

AFRICA

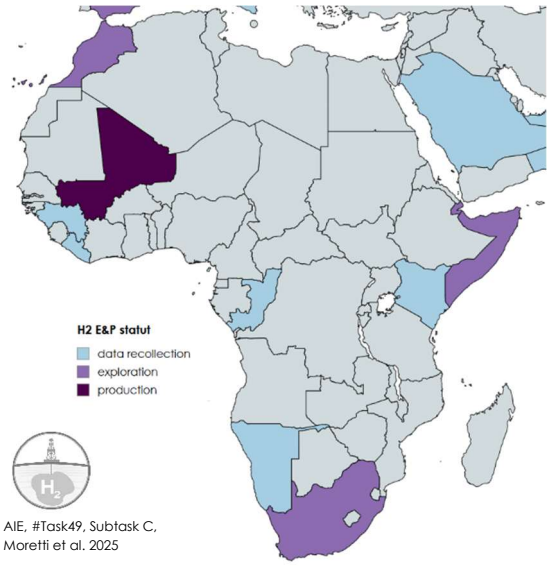

FIGURE 3: NATURAL HYDROGEN EXPLORATION STATUS IN AFRICA BY MID-2025. DARK BROWN: PRODUCTION; VIOLET: EXPLORATION: BLUE: RESEARCH AND PROSPECTION

- One country is producing H_2: Mali
- In four countries the exploration is active: Morocco, Djibouti, South Africa, Soudan.
- Data have been published about the Namibian and East African Rift potential

Mali

The story of the Bourakébougou's discovery is now well known, and it would be superfluous to recount it in detail here, interested readers may refer to [5]. A drilling project for groundwater turned into the world's first natural H_2 discovery and production [6]. Of course, this took time, because it was necessary to understand the geology, change the mining law and persevere, despite all the obstacles that insecurity in this region entails. Because of this insecurity, very few Western scientists have been there, allowing some to harbor doubts and even spread unfounded rumors about the reality of this accumulation. A large dataset is now available that includes wells, petrophysical logs, seismic data and core samples, that have been studied at IFP Energies nouvelles (IFPEN) as part of a PhD thesis, and subsequent peer-reviewed publications [7,8].

More than twenty wells have been drilled after the initial relatively shallow well (110 m) discovery, that proved the existence of four reservoirs, at different depths over a large area. The H_2 origin is not yet clear but GR_2 and 3 are alternative (oxidoreduction and radiolysis). The Neoproterozoic reservoirs are of adequate reservoir quality (over 10%

porosity); with seals comprising both intrusive volcanic rocks dating from the Mesozoic opening of the Central Atlantic and also shales. The H_2 is almost pure (~ 98%) and is currently used to produce the village's electricity, eliminating the need for storage as the H_2 is produced on demand. Scaling up of this production, currently limited, is delayed by the political context, not by the absence of reserves. These reserves have been certified by Chapman in 2020 as a few hundred billion m^3 of H_2 (4 TCF) and then re-evaluated in 2022 after the new drilling campaign (17 TCF).

FIGURE 4: ONE OF THE WELLS IN MALI AND THE FUEL CELL WHICH HAS BEEN USED FOR A WHILE TO GENERATE THE ELECTRICITY OF THE TOWN.

Morocco

Further north, Morocco is evaluating its natural H_2 potential. The Office National des Hydrocarbures et des Mines (ONHYM) is at the center of the work and a number of private European companies are also interested, in particular ENGIE and HYNAT (for the southern province). In 2021, an exclusive contract with HYNAT was signed aiming to investigate the natural H_2 potential of the southern provinces of Morocco. The first results revealed a large number of surface structures showing gamma-ray anomalies and emitting natural H_2 gases with flow rates exceeding 0.1 vol.%. In these structures, the H_2 often occurs associated with remarkable crustal helium (He) concentrations (Fig. 5). At the end of 2023, after starting geophysical surveys, ONHYM and HYNAT announced a first drilling campaign which were scheduled for Q4 2025. At the time, subsurface H_2 accumulations have been reported in seismic data and the monitoring, 2D and 3D seismic survey and drilling planning were still in progress[1] . ONHYM and Storengy also announced an agreement to explore the natural hydrogen potential in the coastal region La Meseta and data for the northern area have been published by ONHYM [9].

[1] https://hynat.com/wp-content/uploads/2024/04/HYNAT-ONHYM-WP2X23-19.09.23-VDef.pdf

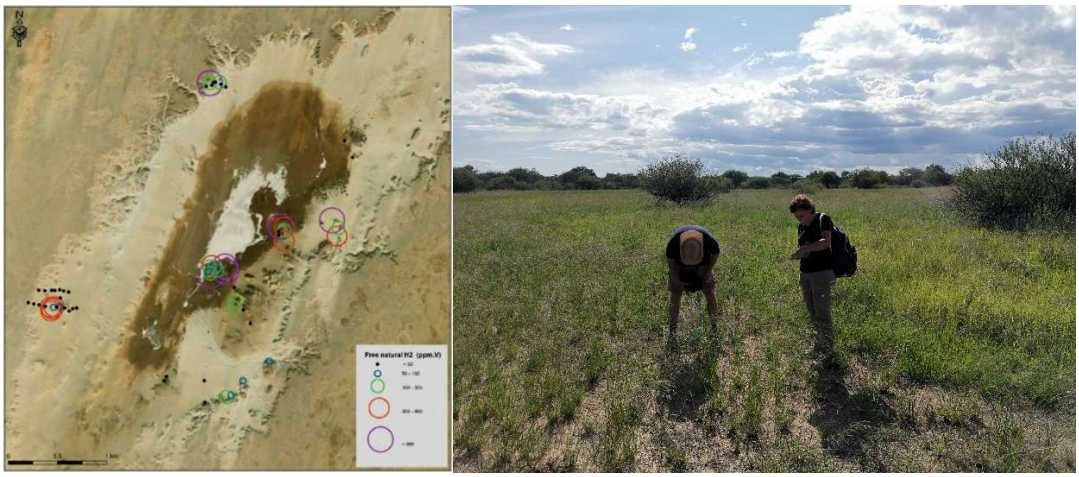

FIGURE 5: LEFT: FIRST RESULTS ON THE NATURAL H_2 EXPLORATION IN THE MOROCCAN SOUTHERN PROVINCES, A SURFACE STRUCTURE WHERE HYDROGEN EMISSIONS WERE MEASURED EXTRACTED FROM A ONHYM PRESENTATION. RIGHT SURFACE STRUCTURE WITH H_2 IN NAMIBIA (RESULTS OF THE MEASUREMENTS IN[10]).

Other African countries

The African continent is rich in cratons (ancient crustal domains containing rocks rich in iron and often in radioactive elements such as uranium, thorium, and potassium, see Fig. 2b & c) and numerous H_2 emanations have been described. South Africa, with its iron and uranium mines, was quickly spotted [11]. These authors favor the hypothesis of radiolysis as H_2 origin (GR_3) since He is also reported. The company Rhinoresource[2] announces to be exploring for H_2 and He, but details are unknown. They have seven onshore exploration permits in the Karoo Basin, at the vicinity of Pretoria. H2Au[3] granted three permits for Technical Cooperation Permits (TCP) in the Pretoria's area, while other companies such as Panoro Energy and iMbokodo Exploration and Production hold licenses to explore known higher concentrations of He in the basin.

The neighboring Namibia, with its mines and Neoproterozoic Banded Iron Formations (BIFs), GR_2, also has very good potential [10][12] but the regulation to take H_2 exploration permit is not clear so far.

The Long-Term Joint European Union-African Union (EU-AU) Research and Innovation Partnership on Renewable Energy (LEAP-RE) has recently started an international research collaboration focused on natural hydrogen occurrences in Africa[4]. Referred to as HyAfrica, the project teamed up researchers and professionals from Europe and Africa and is focused on South Africa, Morocco, Mozambique and Togo. The aim of HyAfrica is to access the natural H_2 resources in the chosen countries, evaluate their socio-economic impact and support future exploration programs. The project reported natural H_2 surface

[2] www.rhinorsc.com
[3] https://www.h2au.co/
[4] https://www.leap-re.eu/hyafrica/

emissions in Mpumalanga (South Africa), however, no complete results have been published so far[5].

Along the East African Rift, Crust and lithosphere are thinned, raising the question of H_2 generation similar to that of the mid-ocean rifts. Missions to the Republic of Djibouti and Ethiopia in particular have helped to clarify this hypothesis. While the quantity of H_2 found is not enormous, it is systematically present in the gases of areas targeted for geothermal energy, and co-production is to be studied [13,14]. ODDEG, Office Djiboutien pour le Développement de la Géothermie, started working on the topic.

High level screening work has been undertaken by Hydrogenesis in Senegal, The Gambia, Guinea-Bissau, Republic of Guinea, Liberia, Ghana, Republic of Congo, Tanzania and Kenya. The company has been working with local governments/data holders to gain access while providing technical deliverables back to the respective countries that can be used to attract further attention towards natural hydrogen via potential bid rounds.[6]

Asia and Oceania

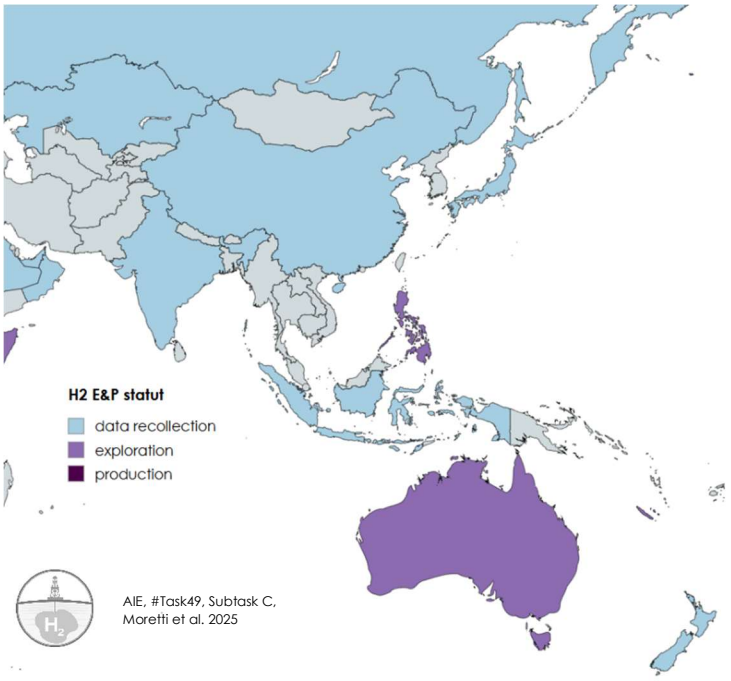

FIG 6: ACTIVITY IN ASIA AND OCEANIA BY MID-2025

- Exploration is active in Australia and Philippines
- Data has been published in Indonesia and in China
- In Kazakhstan the government founded large projects to evaluate the country potential.
- Literature shows that the topic is now studied in India

Australia

With its large mining and oil & gas industries, Australia is a textbook case for the emergence of this sector. In 2019, field acquisition was banned due to Covid and systematic mapping of fairy circles (Sub Circular Depressions -SCD) was undertaken using

[5] www.leap-re.eu/hyafrica/
[6] HydroGenesis – A New Beginning in Hydrogen Energy

satellite images. A correlation between these potential emanations and the cratons of southern and western Australia soon became apparent [15].

Australia has exceptional management of its subsurface data, all is public, and the existence of wells that have already found H_2 near where the SCD are visible (e.g., Kangaroo Island, York Peninsula) also quickly came to light. The idea was of great interest and Australia's National Science Agency (CSIRO) and Geoscience Australia (GA) took up the subject [16,17]. GA quickly published an assessment of the annual flux expected for Australia given the characteristics of the outcropping rocks and published the first data on the H_2 potential of the coals and other organic-rich rocks of the Cooper Basin in Australia [18,19], while CSIRO started to produce research studies on hydrogen generation in geofluids and modern seeps [20,21].

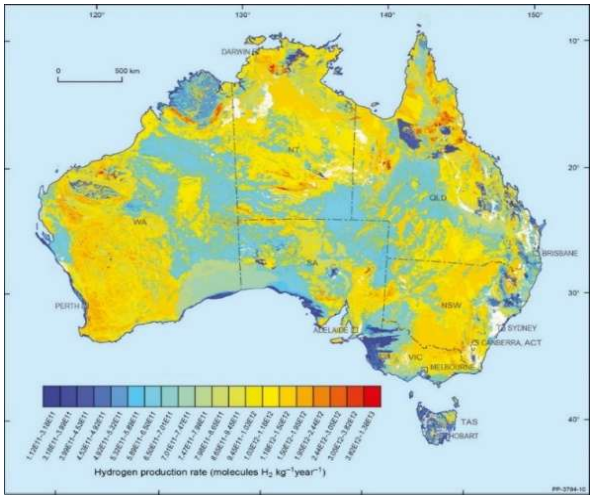

FIGURE 7. MAP OF H2 FLUX IN AUSTRALIA, MADE IN 2020 AND TAKING INTO ACCOUNT ONLY RADIOACTIVITY AND IRON-RICH ROCKS. IN RED AREAS, IT CAN EXCEED 1,013 MOL/YEAR, I.E. AROUND 6% OF CURRENT WORLD CONSUMPTION. SOURCE [19].

South Australia State government (the country being federal) has initially adapted its Petroleum and Geothermal Energy Act 2000 to include hydrogen as a 'regulated substance' and, from February 2021, it became possible to apply for H_2 exploration licenses. Western Australia, the biggest state in Australia and by far the biggest oil and gas producing state, has also seen a new bill passing parliament in May 2024 that enables exploration for naturally occurring hydrogen through the concept of a regulated substance. The other Australian States and Territories are currently working on amending regulations.

The first company to apply for an exploration license in south Australia was Gold Hydrogen, applying acreage around the wells that had already found H_2 between the 1910s and 1930s [22] (up to 80% pure for Ramsay Oil Bore 1 the York Peninsula, SARIG) . Other companies such as H2EX and 2H resources, Buru Energy Limited oil company spin-offs, have acquired acreage. Since then, requests for licenses have multiplied to such an extent that the government has ceased over-the-counter distribution and now wants to offer competitive bid rounds like other raw materials.

Gold Hydrogen is an ASX listed start-up which was created as soon as the potential of this resource began to emerge [7]. The exploration teams have worked for a long time in the Mining and Oil & Gas industries, raised funds and drilled their first two wells in the Ramsey prospect at the end of 2023. The company announced H_2 in 4 reservoirs and helium in the deepest one, which had not been reached in the historical wells of the beginning of the 20th century.

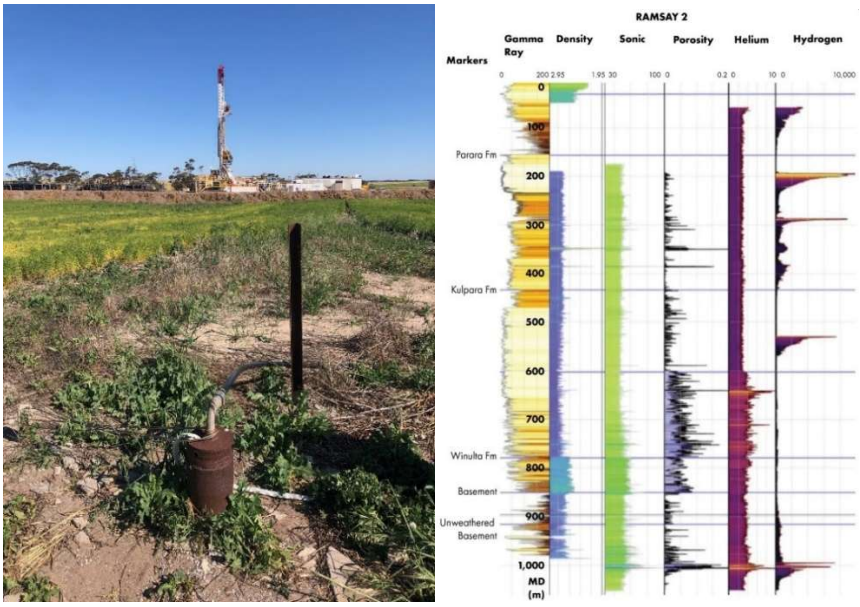

FIG 8: LEFT: PICTURE OF THE HISTORICAL WELL LOCATION AND RIG OF THE NEW ONE. RIGHT: LOG OF RAMSAY SHOWING THE 4 H_2 BEARING RESERVOIRS. GOLD HYDROGEN, YORK PENINSULA.

Further north, in the Amadeus Basin, the Santos oil company, while searching for Hydrocarbon (HC), found a CH_4, H_2, He blend that has already been mentioned [23]. This basin is partly Neoproterozoic and the cover is a salt of this age, although the structures are anticlines formed by slightly later compression [24]. This was not exactly what Santos were looking for at the outset, and the reservoirs in their initial three wells weren't substantial. They took time to think things over, teamed up with a company specializing in helium, and drilling was set to resume.

In the west of the country, as already indicated, the law has not yet been promulgated, but evaluation activities have already begun, with CSIRO on the research side [17] and the Perth University [25]. Some companies having Oil &Gas licenses are also having a better look on this additional resource. The Perth Basin, the Greenstone belt, and the BIF Hamersley Range are all areas of interest. Additionally, the research is active in Australia often with the help of private compagnies as for instance the 2H resources/CSIRO large scale H_2 monitoring project.

[7] https://www.goldhydrogen.com.au/

Philippines

In early 2024, the Philippines launched the world's first competitive bid round. The two proposed licenses are located on the Luzon island. The deadline was August 27, 2024. This area, which has many similarities with New Caledonia and Oman, had already been studied by IFPEN, among others **[26]**. The gases in the emanations are a mixture of H_2, CO_2 and CH_4, with H_2 accounting for around 50%, the flow is strong [27]. According to statements by the Philippine Department of Energy (DoE), numerous American, Australian and European companies have expressed interest in the project[8] and KOLOMA granted two of the licenses.

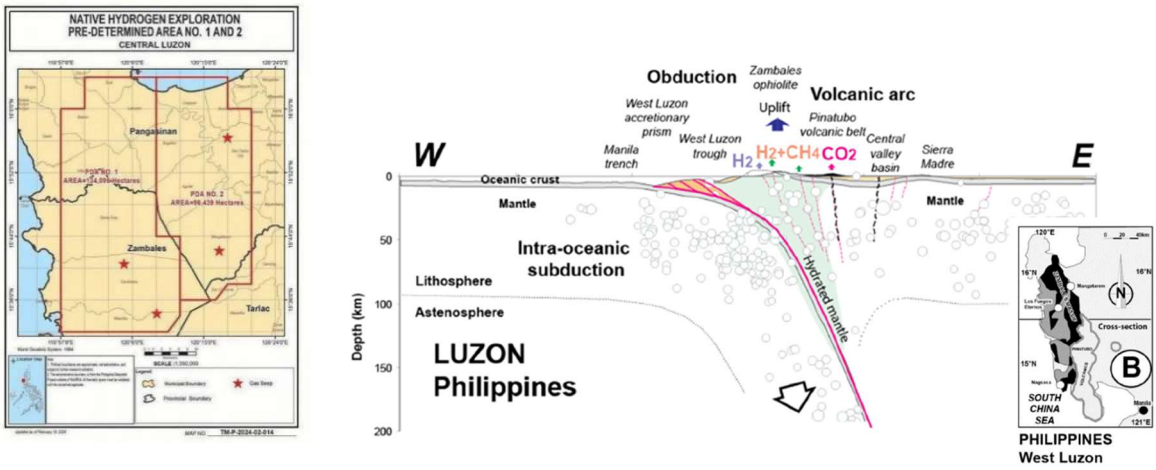

FIG 9 : PHILIPPINES H_2 SYSTEM ACCORDING TO [26] AND AREA OF THE LICENSES OFFERED BY THE GOVERNMENT IN THE 2024 BID ROUND.

China

Currently, Chinese universities and Sinopec are publishing many articles on natural H_2 **[28]**. A scientific well has been announced in October 2025 in Inner Mongolia and was already spudded by the end of October. The well target is in the Erlian basin and the operations have been carried out in cooperation among the Peking University Ordos Energy Research Institute, and the Inner Mongolia Jinqing Geological Exploration Company, Ningxia Baofeng Energy Group Company, China National Petroleum Corporation (CNPC), China Geological Survey and other partners. Articles have been published on the potential of the Songliao Basin (NE China), with H_2 generation from the late maturation of a petroleum source rock **[29]**. This basin hosts c. 7 km-thick sedimentary covers and large H_2 ratio have been reported in the wells, up to 20% **[30]**. Horsfield and coauthors estimate resources up to 4.6 Gt of H_2 just for this basin, GR_4 Figure 2. China is obviously rich in coal, being the world's leading producer, and is also interested in in-situ coal combustion **[31]**. It could enable the country to continue producing H_2 from this type of rock, but without the mining that makes its Life Cycle

[8] https://manilastandard.net/business/314460239/hydrogen-blocks-exploration-gets-investor-interest.html

Analysis so unsustainable. The H_2 potential generation of coal is very high since it linearly increases with the Total Organic Carbon content [32].

Other Asian countries

The last few years have seen the emergence of publications on H_2 as an energy source from various other Asian countries, in particular Indonesia, Vietnam and Korea.

Indonesia

Indra Sanjaya from the Ministry of Energy and Resources (ESDM) has identified H_2 emanations in the Sulawesi ophiolites [33]. The gas is a mixture of H_2, nitrogen and methane. The flow near the beaches is very high, and permanent fires attract visitors who come to picnic. If the geological context is similar to that of the Philippines, we don't know whether the Ministry, or the state oil company Pertamina, are considering exploiting this resource.

Japan

The Japan is short in energy primary sources and the Japan Organization for Metals and Energy Security (JOGMEC) see the natural H_2 as an opportunity[9]. Ophiolites are present in the Archipelago where H_2 has been already reported in hot springs (Hakuba). In parallel 3 large Japanese companies: Mitsubishi Gas Chemical Company, Toyota Motor Corporation Hydrogen Factory and ENEOS Xplora have invested A$14.5 million in Gold Hydrogen Limited in July 2025.

By mid-2025, many indices show that **India** is working now on the topic [34] and the **New Zealand**, which have now H_2 emanations (Poison Bay[10]) in the ophiolites nappes of the south Island also started to evaluate this resources

Middle East

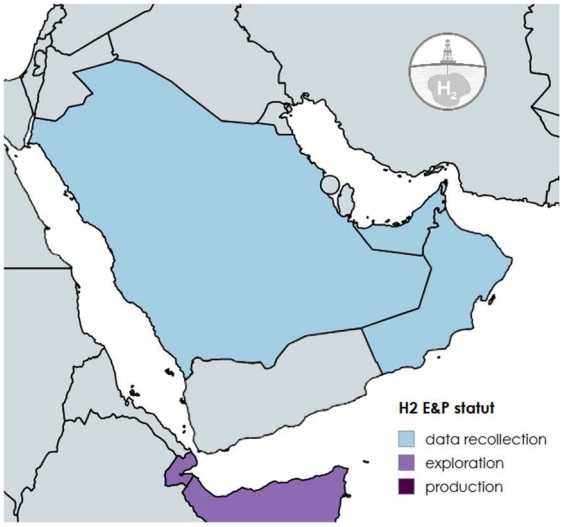

FIG 10: ACTIVITY IN THE MIDDLE EAST EARLY 2025

- H_2 presence is known is Oman, the country is doing well tests for stimulated H_2
- UAE and Saudi Arabia evaluate their country potential

[9] https://www.jogmec.go.jp/content/300393409.pdf
[10] https://www.gns.cri.nz/news/is-natural-hydrogen-our-next-energy-solution/

Oman

H_2 emanations have been detected in Oman's ophiolites for a very long time. [2,26,35]. Scientific wells (Oman Drilling Project) have been drilled and cored. The possibilities of low-temperature serpentinization were highlighted, as was the natural sequestration of atmospheric CO_2 in blue pools (Small puddles of water with high pH levels, due to H_2 emissions, which become coated with carbonate and reflect the blue of the sky). Today, on the pilot and production side, everything seems to be moving towards stimulated hydrogen trials, and there is no information on the exploration of natural H_2.

An agreement was signed between the USA and Oman in 2023 under the auspices of political bodies on both sides (DOE for the USA side, Ministry for Oman) to test stimulated H_2 production in the Semail ophiolites. The EDEN[11] company will set up a pilot laboratory with 4 duplicates of two wells near Muscat. On the research front, the University of Colorado is at the forefront [36]. In addition to water injection, the project is testing electrical stimulation to increase the contact surfaces between water and minerals. An electric arc is created between two wells, and the fractures created by this technology are expected to be better controlled than those of hydraulic fracturing.

UAE

Since the United Nation Conference of Parties, COP28 in Dubai in 2023, there has been an acceleration in the Emirates' interest in renewable energies, and natural H_2 is taking advantage. The Semail ophiolites stretch northwards across the emirates of Ras El Khaimah, Sharjah and Fujairah. Abu Dhabi, the largest and richest of these emirates, with its oil reserves managed by Abu Dhabi National Oil Company (ADNOC), has only the foreland of this assembly line. Initial data acquisition is underway. Université de Pau et des Pays de L'Adour (UPPA), for example, has been working with Rakgas, the Ras Al Khaimah state oil company [37]. The country is also considering ways of enabling exploration and attracting exploration companies to the area. ADNOC is also working on the evaluation of the Abu Dhabi territory.

Saudi Arabia

Saudi Aramco has commissioned studies on H_2 in the kingdom. There first publications explore the potential of the serpentinite of the Peninsula for H_2 production [38], but the subject seems to be of importance both for their research center in Houston and in Arabia. The presence of cratons, Proterozoic rock assemblages and granites in the Saudi territory are promising elements.

[11] https://www.edengeopower.com/

South America

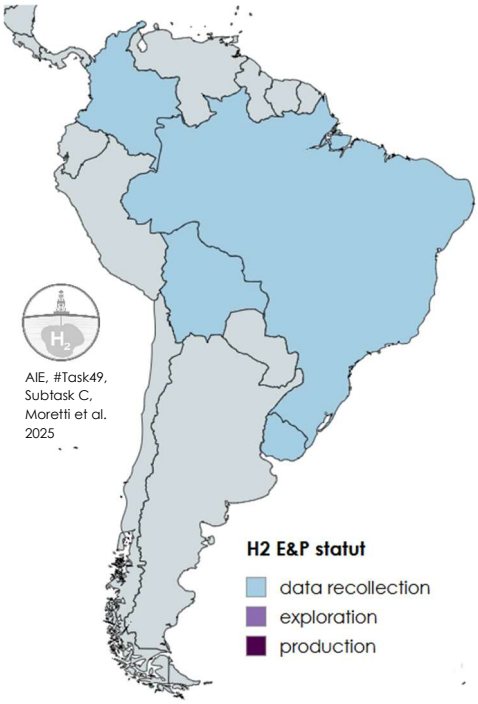

FIG 11: ACTIVITY IN SOUTH AMERICA EARLY 2025

- The Colombian, Uruguayan and Brazilian governments are working of the regulation but there is no permitting yet.
- Data has been published for Brazil, Colombia, Bolivia
- The large cratonic areas of Brazil look very promising

Brazil

Until now, Brazil, with enormous mineral resources, has been at the forefront of H_2 exploration in South America. Natural H_2 gases have been reported in different areas, either as surface emissions or gas shows in old hydrocarbon wells [39–42]. Most of the shows are associated with Proterozoic to Paleozoic strata of intracratonic basins, with a few examples directly associated with ancient metamorphic and magmatic rocks [43]. But for the past three years, the country has been slow to change its law. While waiting for appropriate exploration laws, various companies (GEO4U, ENGIE/Storengy) continue to work and acquire surface data, and the number of surface emanations with proven H_2 content is growing. Most of the reported emanations and subsurface occurrences are concentrated in the São Francisco Basin, where numerous H_2-emitting SCD's were discovered and HC wells had found up to 40% of H_2 [39,44]. The basin is an intracratonic depocenter hosting Paleoproterozoic to Mesozoic strata and igneous intrusions, underlain by an Archean to Paleoproterozoic basement [40]. Natural H_2 sources are apparently located in this basement, which is partially exposed in the Quadrilátero Ferrífero (Iron Quadrangle), one of the largest mineral provinces of the world and where H_2 emanations have been also studied since 2018. Numerous publications point out that basins other than the San Francisco are also very promising, such as the intracratonic Parana to the south [45] and basins in the Amazon craton to the north. In these cratonic basins, intrusions are present cutting the sedimentary successions and banded iron formations (BIFs) and other iron-rich units made up the old Precambrian basement, thus, the geographic areas of potential H_2 presence are enormous. Traces of H_2 emanations are present in much of the country. More recently, evidence of H_2 and He seepage on a

fault affecting Neoproterozoic metamorphic rocks at Marica, on the coast near Rio de Janeiro, has been found [43]. It has attracted a great deal of interest due to the proximity of potential consumers and major ports. An agreement was even signed between various players, including a French H_2 bus manufacturer, in the presence of Presidents E. Macron and Lula in early 2024. Since a new team of politician leaders at Marica slowdown the project.

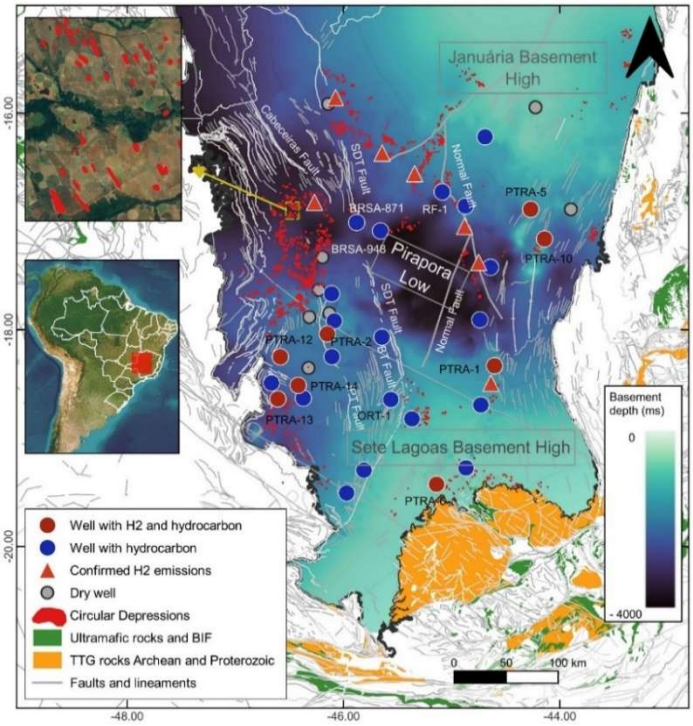

FIG 12: SOUTH OF THE SAN FRANCISCO BASIN SHOWING THE DENSITY OF STRUCTURES SUGGESTING H_2 ESCAPE. THE WELLS WHERE H_2 HAVE BEEN ALREADY FOUND AND THE POTENTIAL GENERATING ROCK [44]. THE NORTHERN PART OF THE BASIN WAS NOT STUDIED IN THIS STUDY BUT ALSO HAS ALSO HIGH POTENTIAL.

Although specific laws on natural H_2 exploration have not been approved so far, Brazil has advanced its regulation of low-carbon H_2 as a clean resource. A law approved by the Brazilian lower and higher Houses and the President in 2024 establishes the conditions and incentives to research, produce and commercialize low-carbon H_2 in the country. With a share of more than 90% of renewables in its electric energy demand (hydro, wind and solar power), Brazil aims to stimulate the production of H_2 to support internal industrial, petrochemical, agricultural and service demands and, ultimately, become a major exporter. In 2022, the National H_2 Program Work Plan has already listed the natural H_2 as a low-carbon resource. The major national oil and gas company, Petrobras, has also announced this year investments of more than U$ 3 MM on the natural H_2 research. Together with the ongoing geological investigations, the recent laws and strategic changes in the country are paving the official exploration of this resource, however to yet started by mid-2025.

Colombia

At the same time, in Colombia, the Pedro's government is making H_2 *blanco* (white) a national priority and encouraging companies explore this resource. In 2023, the Minister

of Mines and Energy, Irene Vélez Torres, consistently presented it as the new carbon-free natural resource, to such an extent that even scared the traditional HC players and their employees, in a country where oil production is a major contributor to the trade balance. The law was due to be promulgated in 2023 and by mid-2025 is still ongoing. Geologically, there are ophiolites in the western part of the country (Western cordillera, Cauca valley; [46]), ferro-nickel mines and carbon resources . Eastward in the Llanos Orientales and Caguán-Putumayo basins, H_2 indices have been also found by the state-controlled oil and gas company, Ecopetrol **[47,48]** and the Agencia Nacional de Hidrocarburos (ANH)[12] reported indices in the northern part of the country

The Ministry of Science launched a call for projects at the beginning of 2024. Applications must be submitted by July 2024, and at least 3 projects in the million-dollar range have been selected (national universities of Medellin and Bogota were first ranked in this concours). In a recent interview, an authority of the Colombian Hydrocarbon National Agency (ANH) has indicated plans for a bid round offering areas to explore natural H_2. These areas may include prospective regions in La Guajira to the north, the Eastern plains and Eastern and Central Cordilleras.

Others

Compared with its neighbours, Uruguay is a small country with a low-carbon energy mix thanks to hydroelectric and wind power. Its H_2 roadmap was classically linked to its potential surplus green electricity generation capacities. In 2024, however, the first company fully dedicated to natural H_2 in the country and South America was created: Nativo Energy[13]. A mission carried out with French geologists revealed many emanations (the bedrock is partly Archean, partly Neoproterozoic in age) and discussions are underway to obtain a mining estate. The University of Montevideo has a small group of young researchers, including two PhD's dedicated to this subject [49]. The first bid round is announced for 2026, or early 2027, by ANCAP[14] the national agency in charge of the oil and gas exploration licensing.

In the Andean countries, Bolivia and Peru in particular, there have been a few publications and occurrences of H_2. Campaigns have been carried out, in particular by the University of Grenoble and UPPA, but no progress has been made in terms of regulation. The H_2 identified seems to be linked to subduction of the Pacific plate underneath the South America continent [50].

[12] Agencia Nacionale de los hidrocarburos
[13] https://www.nativoenergy.com/
[14] https://www.ancap.com.uy/

North America

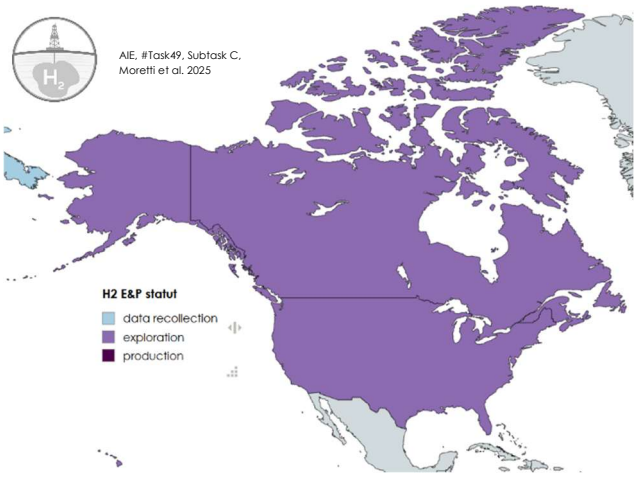

FIG 13: ACTIVITY IN NORTH AMERICA EARLY 2025

- Exploration started in US and Canada
- In both countries many young /small compagnies are rising founds and start exploring
- US is the place of the world where the activity is the strongest

USA

Early detailed evidence of widespread anomalous amounts of natural H_2 in the United States were firstly published in the 80's, after analyses of gases produced from multiple hydrocarbon wells drilled in Kansas, at the Midcontinent (e.g., **[51]**). Geochemical, petrophysical and petrographic studies conducted on these shows and other reported afterward revealed an origin associated with hydration reactions of iron-rich rocks of the metamorphic and variable mixtures with crustal helium, metamorphic nitrogen, thermogenic and microbial hydrocarbons **[51,52]**. The first exploration data focused on H_2 was conducted in surface depressions of North Carolina and indicated anomalously high H_2 flows [53] and then the geoscientist get focused on the mid continental rift . The United States Geological Survey (USGS) is currently evaluating country's potential for natural H_2 exploration and developing a software to quickly estimate the potential production of H_2 GR_1 and 3 [54].

As of 2019, NH2E, led by Dr. Viacheslav Zgonnik, has drilled its first well in Nebraska, and although the data has remained confidential, it was announced as positive. Once again, the Covid-19 period travel restrictions has slowed down the activities, but now the Australian company Hyterra[15] has teamed up with NH2E and the well is now being tested. An H_2 flame is very hot but invisible, thus, only thermal camera images allow us to visualize it (Figure 14). Further west in Arizona, Desert Mountain has already drilled 8 wells with He and H_2 targets. They have announced that they have found a mixture of 90% nitrogen and 5% each of the other two gases, He and H_2, and production is due to start in 2024[16]. The data indicate an economics based on helium concentrations and increasingly profitable market.

[15] https://hyterra.com/
[16] https://www.desertmountainenergy.com/

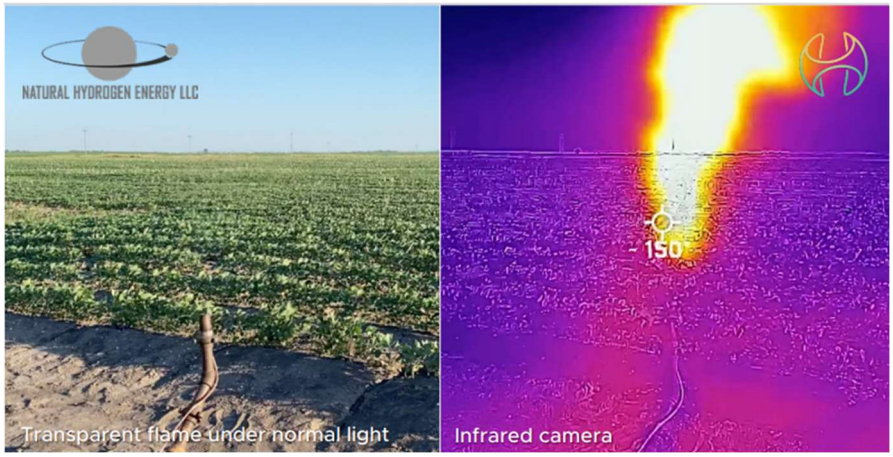

FIGURE 14. REAL LIGHT AND INFRARED PHOTO OF A PRODUCTION TEST ON THE NHE COMPANY WELL, IMAGE OF THE HYTERRA SITE

A remarkable spotlight on US natural H_2 exploration was given by the startup KOLOMA, which raised more than U$400MM from the government and companies of different segments for exploring natural H_2 in the country. Even future low carbon H_2 consumer as a truck constructer invested in the company. According to its own description, Koloma "is a geologic H_2 company that leverages its technology, proprietary data, and human capital advantages to identify and commercialize these resources on a global scale". Other companies such as High Plains Resources and Twin Rivers Exploration, that belong to KOLOMA, are active in Kansas and Iowa respectively, with the former recently acquiring seismic data over the mid continental rift in Kansas.

More recently, the Australian Securities Exchange (ASX) listed Hyterra has been bankrolled via an AUD$21.9million deal from Fortescue, acquiring 39.8% interest in the firm[17] and creating a strategic alliance for future exploration. Post deal Hyterra has drilled two wells and as of July 2025 is commencing with its third well, seen as an appraisal well of the Nemaha Project. Early published results reference H_2 concentrations of 16.5% and helium concentrations of up to 4.4% in the Blythe 13-20 well. Activity has now moved to the McCoy well which is seen as more exploratory in nature given it is not twinning an existing well like the previous two wells did. McCoy is being described as a helium well so it remains to be seen if the mid continental rift will emerge as a H_2 play domain or not[18].

Finally, other organizations such as ARPA (Advanced Research Project Agency) are looking for federate research and perhaps set up a pilot project. This organization, no doubt influenced by the success of shale gas developments in the US, is also considering testing the possibilities of orange H_2. The idea is to produce H_2 by triggering redox reactions on iron-rich rocks. Such nature-mimicking reactions have already been proposed to generate magnetite and H_2 on the surface of waste from the metallurgical industry (Hymag'in

[17] Fortescue counts on white hydrogen with $21.9m investment in HyTerra – HyTerra
[18] StockTake: HyTerra rigs up to spud next Kansas helium well – HyTerra

company[19]) or nickel mine slag in New Caledonia [55]. It has not yet been proven that a process consisting of injecting water into rocks at depth can rapidly generate H_2 in significant quantities, but scientists estimate that the reaction speed will have to be increased by a factor of 10,000. The Department of Energy is investing U$20 million dollars and funding this research via ARPA-E, which awarded national top laboratories, universities and private companies such as KOLOMA and Eden Geopower. The plan is to test catalysts and/or increase the reaction surface area using induced fracturing. Researchers are also being encouraged to file patents. In any case, this type of production is a word away from the "white" H_2 naturally generated without stimulation, even if the characterization of oxidizable iron-rich rocks remains the same. One may note that VEMA[20] a French/American company which works also in stimulated H_2 have an opposite view and consider the frac as counterproductive.

Canada

In Canada, first publications on H_2 potential concentrate on uranium mines [56], although the country also hosts BIFs, ophiolites and Archean ultramafic rocks. Many of these rock assemblages made up the basement and sedimentary covers of the northern North American craton. The Quebec government published a first assessment of its potential indicating twenty-seven potential areas in which natural H_2 would have been generated through different geological processes [57].

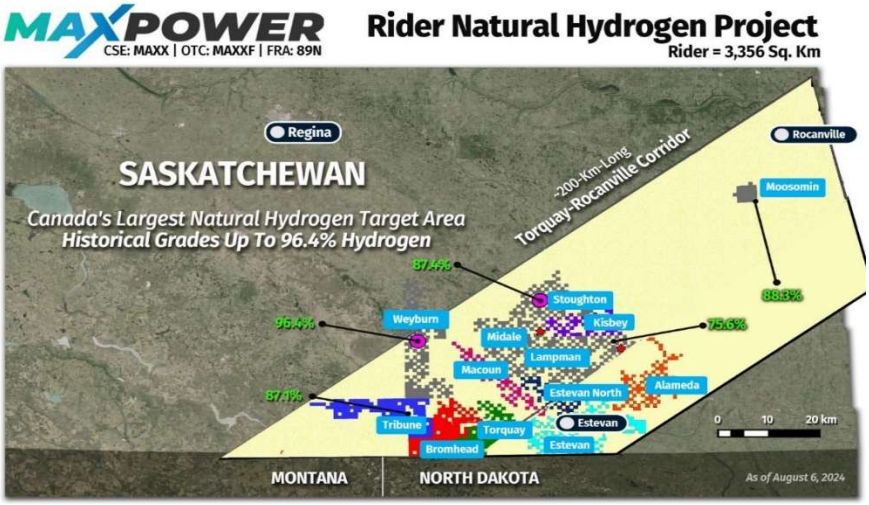

FIG 15: SCREEN OUT OF THE RIDER NATURAL H_2 PROJECT IN THE SASKATCHEWAN PROVINCE. IT WAS ANNOUNCED BY THE MAX POWER MINING COMPANY, BASED ON H_2 SHOWS DOCUMENTED IN OLD HC WELLS[21].

The first step on exploring natural H_2 in the country was made by the Vancouver-based Max Power Mining. The company recently announced the Rider Natural H_2 Project, which intends to explore the low-carbon resource in an area of 3.356 km^2 in the Saskatchewan province. The permits were acquired after an exhaustive analysis of old hydrocarbon wells data that revealed gases with concentrations of up to 96.4% of H_2 (Fig. 15). The company is planning to develop the project with the collaboration of national and

[19] https://www.hymagin.com/
[20] https://www.vema.earth/
[21] www.maxpowermining.com

international partners, including Chapman H_2 and Petroleum Engineering Ltd. and Larin Engineering HHC. The exploratory model assumes the H_2 generation in the basement of the North America craton (especially through hydration reactions in ultramafic and basic rocks), the upward migration through major tectonic structures and potential accumulation in reservoirs of the Western Canadian Sedimentary Basin.

Europe

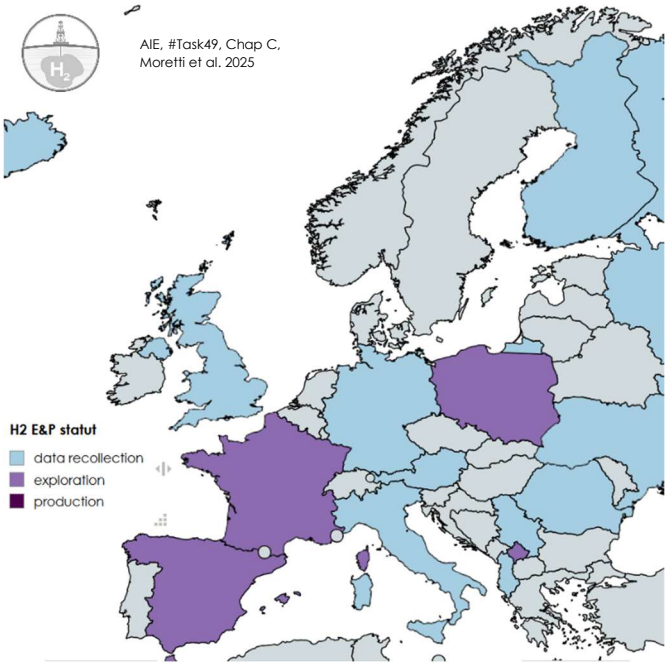

FIG 16: ACTIVITY IN EUROPE EARLY 2025

- First permits in France, 3 already granted in the Pyrenean Foreland, 3 more under evaluation.
- Excellent indices of H_2 dissolved in aquifer in Lorraine.
- A license in Aragon, Spain, but the law remains unclear
- Exploration also started in Poland and Kosovo

France

From a regulatory point of view, France has recognized H_2 as a natural resource since early 2022. The management of natural H_2 permits is regulated at the national level. Companies interested in exploration can choose to apply for either an Exclusive Research Permit (PER in French) or an Exploration Permit (Concession).

A consortium comprising CVA, ENGIE/Storengy, 45-8, BRGM and UPPA is working on behalf of the Nouvelle-Aquitaine region to assess its potential. The project has not yet been finalized, but a first exploration permit has been applied and granted in 2023 near Sauveterre to the company TBH2, in an area where emanations had been highlighted in the PhD thesis of N. Lefeuvre (Grenoble University) **[58]**. ENGIE/Storengy and 45-8 have also granted exploration permits at Landes and Pyrenees. In Lorraine, the company FDE (Française de l'Energie) asked for its first permit following the discovery of promising indications of high H_2 content in gases dissolved in an aquifer (Trois Evêchés, granted by january 2026). 45-8 has also two helium licenses in France, exploration started earlier and the production started mid-2024.

Spain

In 2023, the Geological and Mining Institute in Spain (IGME) recommended to the Ministry of Ecological Transition and Demographic Challenge (MITECO) in an official report that natural H_2 should be included in Section D of the Spanish Mining Law. IGME concluded that natural H_2 is an energy resource and therefore it could not be part of the Section C (geological resources). IGME also pointed out that, natural H_2 is usually associated to other gases. Further clarifications on this regard should be expected from the Ministry of Ecological Transition and Demographic Challenge in Spain. Until that time natural H_2 exploration is likely on hold.

Historically, Repsol Exploration S.A has been also active and conducting research in the field in Spain. The company is currently cooperating with the University of Granada in areas related to the association of natural H_2 to serpentinization.

The most active explorer in Spain is Helios Aragon, holding a significant acreage position in the Southern Pyrenees covering the Monzón Field. Monzón is an interpreted H_2 discovery that was made by Enpasa in 1963. 100% H_2 was recorded in mud gas returns while drilling the pre salt bunter sandstone section that was the original target for this HC exploration well. The well apparently naturally flowed a gas from this section but was later abandoned as the gas was not methane.

The Monzón field has company estimated reserves of 1.1M tons with a further 5-10M tons of prospectivity within the Barbastro and Monzón permits located in the regional Ebro Basin play. The structure is defined by gravity and 2D seismic data and Helios also conducted a geochemical soil gas survey in 2022. It confirmed high levels of H_2 and also helium near the discovery well and it was correlated with subsurface features. The Monzón field has estimated reserves of 1.1M tons with a further 5-10 M tons of prospectivity within the Barbastro and Monzón permits located in the regional Ebro Basin play.

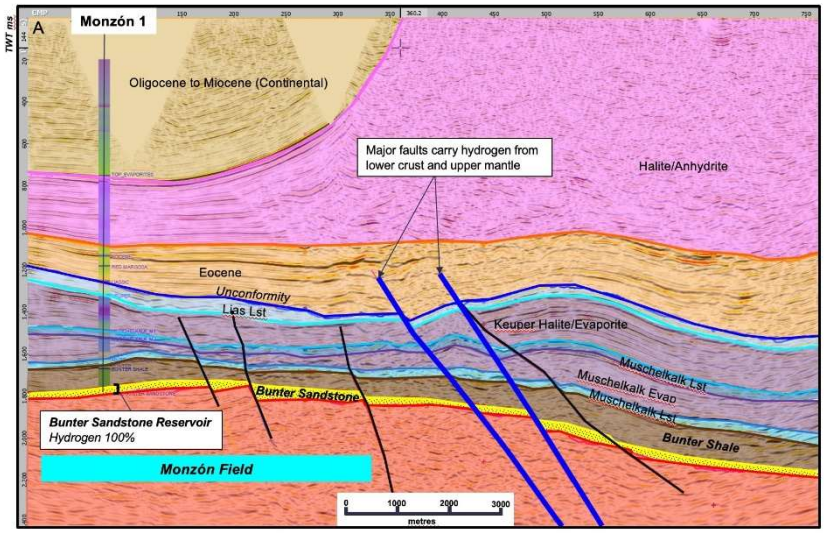

FIGURE 17. HYDROGEN SYSTEM, HELIOS MONZÓN 1 FIELD, 2022

The company plans to invest €12M to drill an appraisal well to confirm the reserve size of Monzón 1. Initially scheduled in Q1 2025, the drilling campaign is now expected in 2026. If the reserves are confirmed as expected, from 2026 to 2028, Helios then plans to continue with the construction of the project and having the first production facility completed in 2029. Helios is currently operating under hydrocarbon permits which allow the company to continue with the appraisal well until the end of the investigation permits. The company has a subsidiary in Poland and currently developing another projects in the country with further interest in Hungary, UK, Oman, and the Philippines.

Hydrogen Age is another startup in natural H_2 exploration and production active in Spain aiming to become a global player in the natural H_2 industry. The Scientific Foundation of the company is based primordially on the Hydric Earth Concept by V.Larin - since 1968. The company has been active also in other countries, such as the USA, where it drilled for natural H_2 in 2019 in Nebraska.

Poland

In Poland, the mining code has included natural H_2 since Nov 2023. To our knowledge, this code has not been updated, but the natural H_2 resource has been added. As a result, permits can now be obtained on a similar basis to hydrocarbon, which obviously poses difficulties for companies. Expenditure commitments in terms of seismic acquisition and wells cannot be of the same order of magnitude. Discussions are nevertheless underway, as the Polish subsurface is promising. Subsurface data is partly public in Poland, and an analysis of old wells shows H_2 concentration values in excess of 60%, particularly in Cambrian reservoirs. The late maturation of coals could also play a role in the country's H_2 potential.

The Polish Geological Institute (PGI) has undertaken substantial work in the field of natural H_2 in the country. The data base in Poland is certainly extensive and it is apparent that PGI has developed an extensive understanding of both the occurrences and potential for natural H_2. The Polish Government has been supportive to the development of natural H_2 in the country however, some challenges that might slower the commercial development is the investment in exploration required by the Government which is the magnitude of the annual license fees for petroleum. Helios Polska (branch in Poland of Helios Aragón) is currently developing a project in the country.

Balkans/Dinarides

The presence of H_2, and abiotic methane, in the Dinarides and Hellenides, mountain ranges involving ophiolitic nappes has long been noted [59,60] although these authors were not interested in H_2 as a primary energy source. More recently, further studies have been undertaken and the French company 45-8 has applied for an exploration permit in Kosovo after exploratory work carried out in partnership [61]. In Albania, large H_2 leakage has been detected in a mine; the flow suggests connection to a large deep reservoir [62].

Germany

There are indications of occurrence of natural H_2 in Germany in places such as, Leupoldsgrün in Upper Franconia, where increased H_2 content in the rock was measured in the 1960s. The Federal Institute for Geosciences and Raw Materials (BGR) is currently contributing to the implementation of the national H_2 strategy with some geoscientific studies focusing on the survey of regional underground storage potential in Germany and the criteria for determining the suitability of underground storage facilities for H_2.

In July 2023, the German Government Federal Cabinet stated regarding the national H_2 strategy that the German government does not see potential in Germany for large-scale extraction of natural H_2. The Government acknowledges deposits in the country but containing only small amounts of H_2, which could lead just to very limited local economic use.

Finland

The Geological Survey of Finland GTK published last May 2024 the first Map of Geological Hydrogen Measurement Results in the country. The results show the percentage of geological H_2 in gases from boreholes, either dissolved in groundwater or as a free gas phase. The research conducted however, has not been carried out with the intention of searching for geological H_2 (Figure 18). More basic geological and geochemical research is expected to be undertaken by GTK to understand the factors that influence the occurrence of geological H_2 in Finland and use this research data to advance towards natural H_2 production.

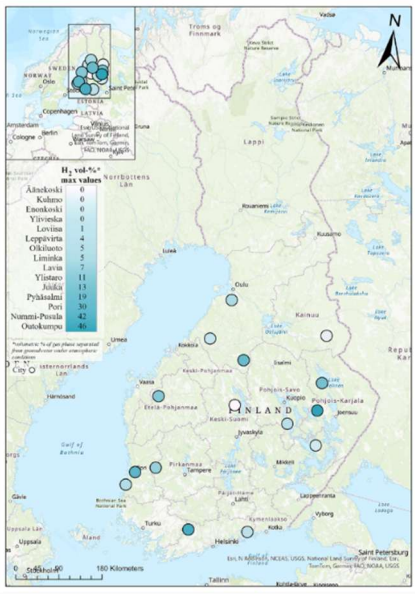

FIGURE 18. GEOLOGICAL HYDROGEN MEASUREMENT RESULTS IN FINLAND

The results show the percentage of geological hydrogen in gases from boreholes (dissolved in groundwater or as a free gas phase).

UK

The British Geological Survey (BGS) on behalf of the Department for Energy Security and Net Zero (DESNZ) of the UK Government, recently published a report on the potential for

Natural Hydrogen in the UK [63]. While the report highlights no known accumulation or seeps of hydrogen in the UK, it does outline areas that may warrant further research.

At this time the only known explorer active in the UK is Desert Mountain Energy, who recently formed Desert Energy UK Ltd and have reportedly secured 958 km^2 of landowner agreement for the assessment of natural hydrogen and helium potential in Devon[22]. Additional notable UK based participants include the AIM listed Getech, a data/service provider with a growing interest in providing solutions towards natural hydrogen exploration. Getech and Sound Energy, another AIM listed company, have recently partnered to explore for natural hydrogen in Morocco[23]. Snowfox Discovery, an Oxford Science Enterprises spin out focused on natural hydrogen exploration, recently closed its first tranche of series A funding attracting investors such as BP and Rio Tinto mining.

Conclusions

The discovery in Mali and the search for low-carbon, cheap hydrogen has led to very strong growth in activity in this field. Depending on the country, the implementation of mining law has been more or less rapid, but overall, between 2020 and 2025, around ten countries have opened up exploration permits and around twenty others have begun to assess their resources.

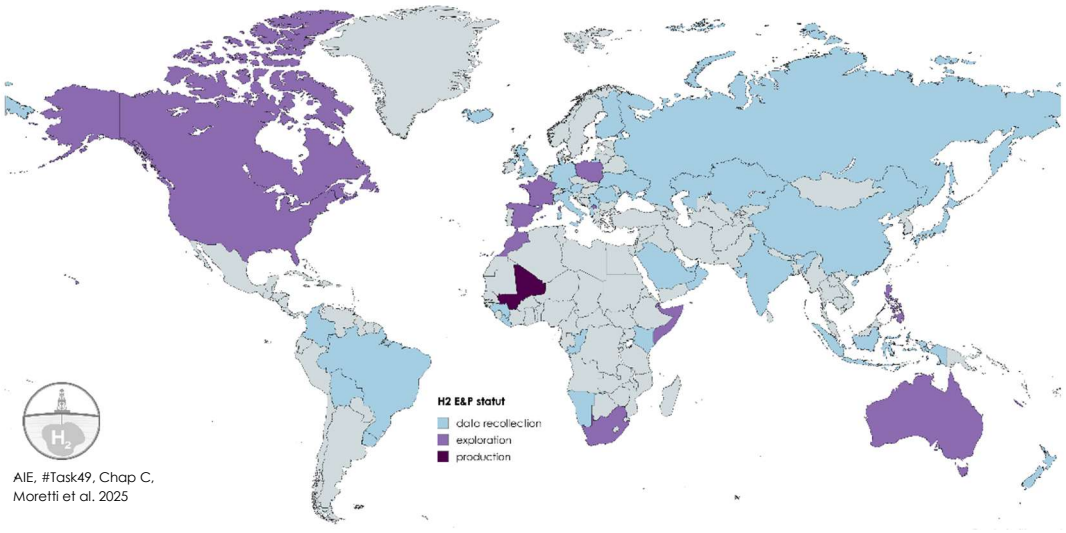

FIGURE 19. SYNTHESIS OF THE WORLDWIDE PROSPECTION AND E&P OF NATURAL H_2

Growth may seem slow to those seeking rapid change in the energy mix, but it is nevertheless very rapid given the complexity of natural resource management and the financial requirements for investment in this area. As of mid-2025, no production outside Mali has been announced, but the field delineation stage has been reached in the US and Australia, which were the first movers.

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