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Natural hydrogen in the energy transition: Fundamentals, promise, and enigmas

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A B S T R A C T

Beyond its role as an energy vector, a growing number of natural hydrogen sources and reservoirs are being discovered all over the globe, which could represent a clean energy source. Although the hydrogen amounts in reservoirs are uncertain, they could be vast, and they could help decarbonize energy-intensive economic sectors and facilitate the energy transition. Natural hydrogen is mainly produced through a geochemical process known as serpentinization, which involves the reaction of water with low-silica, ferrous minerals. In favorable locations, the hydrogen produced can become trapped by impermeable rocks on its way to the atmosphere, forming a reservoir. The safe exploitation of numerous natural hydrogen reservoirs seems feasible with current technology, and several demonstration plants are being commissioned. Natural hydrogen may show variable composition and require custom separation, purification, storage, and distribution facilities, depending on the location and intended use. By investing in research, in the mid-term, more hydrogen sources could become exploitable and geochemical processes could be artificially stimulated in new locations. In the long term, it may be possible to leverage or engineer the interplay between microorganisms and geological substrates to obtain hydrogen and other chemicals in a sustainable manner.

1. Hydrogen in the energy transition

As the world transitions beyond fossil fuels towards a more sustainable and low-carbon future, hydrogen is becoming a key player in the energy mix. Hydrogen is highly versatile, able to power transportation, industry, and buildings, and can help reduce greenhouse gas emissions. While hydrogen has been utilized in industrial processes and fuel cells for decades, as shown in Fig. 1A, recent technological advances and the growing menace of climate change have heightened the interest in hydrogen for decarbonizing the energy system [1,2].

Fig. 1B depicts the demand for hydrogen since 1985. The demand in 2021 stood at 94 Mt (million metric tons), and it is projected to double by 2030, reaching 180 Mt [3,4]. Currently, around 75 Mtpy (million metric tons per year) of pure hydrogen and 45 Mtpy of hydrogen blends, such as syngas, are produced to meet the demand [2,3]. Fig. 1A depicts the various sources of hydrogen production in 2021, highlighting that most hydrogen production comes from fossil fuel reforming, with only a small portion derived from alternative sources like electrolysis. At present, the cost difference between these processes is represented in Fig. 1D, with hydrogen produced from fossil fuels (grey hydrogen) costing $1.2 per kilogram compared to $4 per kilogram through electrolysis (green hydrogen) [10,11]. Over time, however, it is expected that the costs associated with electrolyzers will decrease, that solar electricity will become cheaper, and that raw material costs in fossil fuel reforming will increase (Fig. 1E), favoring electrolysis. Apart from cost, the carbon footprint associated with fossil fuel reforming, even with carbon capture and utilization technologies (CCUs), is considerably higher than that of electrolysis, which makes electrolysis a more

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environmentally friendly option (Fig. 1C) [5–7].

Recently, a third approach has emerged in the field: natural hydrogen. This refers to naturally occurring molecular hydrogen that forms and accumulates on Earth. For decades it went unnoticed, as it was assumed it would be formed in too small amounts or diffuse away too quickly. Moreover, analytical methods used in field studies were often not suited to detect this gas. Today, however, it is gaining popularity among scientists, entrepreneurs, and ecologists. Current estimations suggest that approximately 20 Mtpy of natural hydrogen are escaping from the surface into the atmosphere [12]. Most of this hydrogen travels up to the ionosphere and ends up escaping into space [13–15]. The genesis of natural hydrogen is primarily attributed to a geochemical process known as serpentinization (see section 2). It was long believed that natural hydrogen deposits could not be formed, and, to date, no large-scale exploitation of geological hydrogen has been carried out. However, this view has changed with studies conducted in geological formations where hydrogen release occurs continuously [12, 16–19]. These studies have confirmed the presence of vast geological formations where hydrogen accumulated over time. Moreover, the pioneering exploitation carried out by Hydroma in Mali (West Africa) has demonstrated the potential for industrial-scale exploitation of this resource. Consequently, it is reasonable to think that substantial amounts of already-produced hydrogen could be trapped throughout the globe.

Besides natural hydrogen, another hydrogen source produced from geological substrates is being considered: orange hydrogen. Natural hydrogen (also referred to as gold, white, or native hydrogen) is hydrogen produced deep within the Earth that becomes trapped by impermeable barriers on its way to the atmosphere, similar to the way petroleum was stored over time. On the other hand, orange hydrogen results from the anthropogenic stimulation of the same geochemical processes that produce natural hydrogen. From an economic standpoint, the supply of raw material (water) occurs through water infiltrating or being redirected from the surface or from bodies of water. The required energy is naturally provided by the environment as geothermal energy. These factors are particularly important, since the main economic

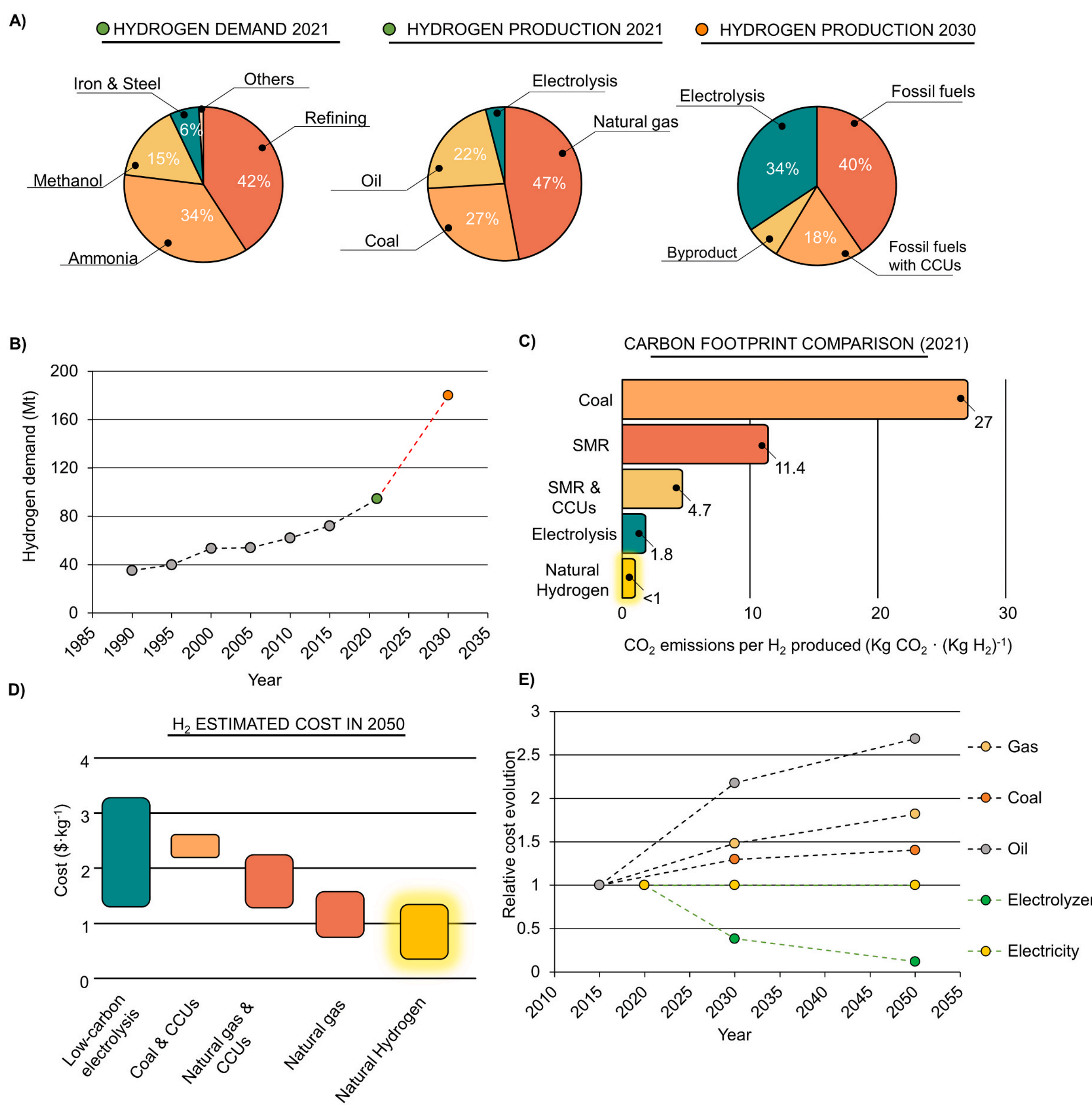

Fig. 1. **A)** Hydrogen demand and production in 2021 and 2030 [2,3]. **B)** Evolution of hydrogen demand from 1990 to 2030 [4]. Grey, green, and red colors represent past, current, and future estimates, respectively. **C)** Carbon footprint for H_2 production processes (2021) [5–7,8]. **D)** Global projected hydrogen production cost (2060) [9]. Note that the data originates from a company with interests in the sector. **E)** Evolution of key cost drivers of electrolysis and fossil fuel reforming [5–7].

challenges for current hydrogen production processes are the supply of raw materials (in fossil fuel reforming) and the energy costs (in electrolysis). Although more studies assessing the carbon footprint of natural and orange hydrogen are needed, their carbon footprint can be lower than that of current approaches (Fig. 1C) [8].

This document aims to introduce natural hydrogen and orange hydrogen in an accessible manner to a broad audience. Section 2 presents the topic of hydrogen formation deep within the Earth, with a specific focus on one of the primary abiotic reactions, known as serpentinization. Additionally, biological processes and their potential contributions to hydrogen production are mentioned. Section 3 takes a practical stance by considering various known deposits, methods of detection, and profiling industrial players in the field. In Section 4, the extraction, storage, and distribution process for natural hydrogen is surveyed, including specific considerations on orange hydrogen. Lastly, we share some perspectives on the future of this field.

2. Formation of hydrogen in nature

The formation of natural hydrogen is showed in Fig. 2 and can involve multiple processes, including biological processes (e.g., decomposition of organic matter, fermentative processes) and abiotic processes (e.g., radiolysis, direct H_2O reduction), with serpentinization being the most significant abiotic process [20]. Serpentinization occurs when water interacts with ultramafic rocks [21], which are low-silica rocks rich in reduced metals. They primarily consist of iron and magnesium minerals, with olivine being the main constituent. Olivine is a solid solution of fayalite (Fe_2SiO_4) and forsterite ($MgSiO_4$). Other components may also be present, such as pyroxene.

Ultramafic rocks make up the Earth's upper mantle, the top section of which is part of the lithosphere. It underlies the more silica-rich crust, and it fractures when mechanically stressed. Serpentinization reactions take place when water infiltrates the Earth's lithospheric mantle along these fractures. These processes are common along plate boundaries, such as mid-ocean ridges, transform faults, and subduction zones. Ultramafic rocks are also common in ophiolite complexes and in fold belts that represent sutures between collided tectonic plates. When water-exposed ultramafic rocks undergo serpentinization, hydrogen is produced as a byproduct [21].

The serpentinization of olivine, shown in Fig. 3, involves two main reactions: hydration and oxidation. The hydration of olivine produces new minerals, such as serpentine ($Mg_3Si_2O_5(OH)_4$) and brucite ($Mg(OH)_2$). Serpentine can incorporate only small amounts of ferrous iron and most of it is oxidized by water to form magnetite (Fe_3O_4), producing H_2 in the process. Ferrous brucite may be an intermediate phase in the process [22–24]. Depending on the bedrock composition, the serpentinization process can be much more complex, as the presence of heteroatoms (e.g., Ni and C) introduces additional phases and reactions (e.g., formation of Ni_3Fe and Fe_5C_2) [25].

A critical property of ultramafic rocks that enables substantial H_2 production is their low silica content, which results in the formation of alteration minerals that largely exclude Fe^{2+} from their structure, like serpentine and brucite. This enables oxidation by water and the formation of H_2 (Schikorr reaction). In contrast, silica-rich rocks like basalts tend to sequester a greater proportion of Fe^{2+} in silicate alteration minerals such as chlorite and amphibole, which readily incorporate Fe^{2+} into their structure instead of converting it to Fe^{3+}. As a result, the hydrothermal alteration of basalt generates much lower amounts of H_2 compared to the serpentinization of ultramafic rocks, despite basalt having a higher Fe^{2+} content [26].

The rate of serpentinization of the parent rock is mainly controlled by three variables: temperature, pressure, and the water-to-rock mass ratio. The optimal temperature range for the process is between 200 and 300 °C [27]. Experimental studies at low pressure (≤500 bar) show that

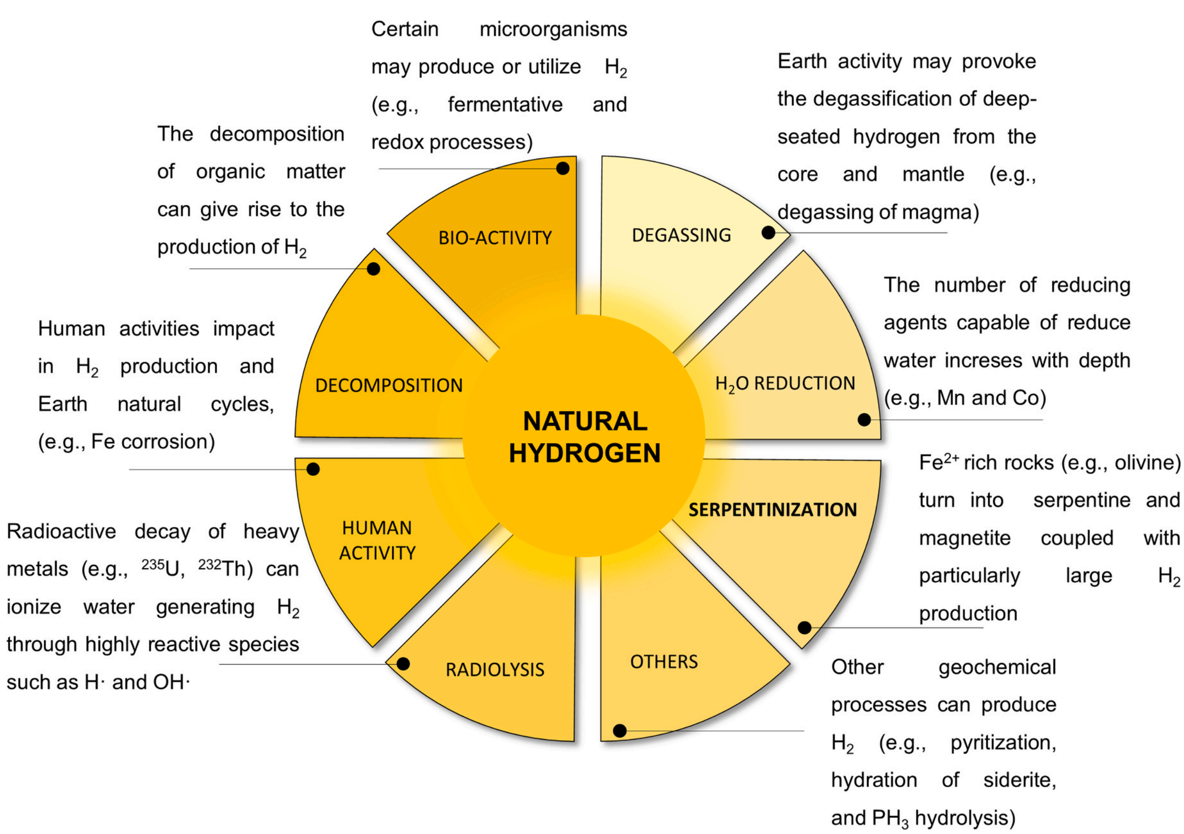

Fig. 2. Different hypotheses about the origin of natural hydrogen deposits [12]. Although the formation of natural hydrogen seems to have a primarily abiotic origin, other theories about its genesis are being considered. Investigating the sources and mechanisms of its formation is key to the long-term exploitation of this resource in a sustainable manner.

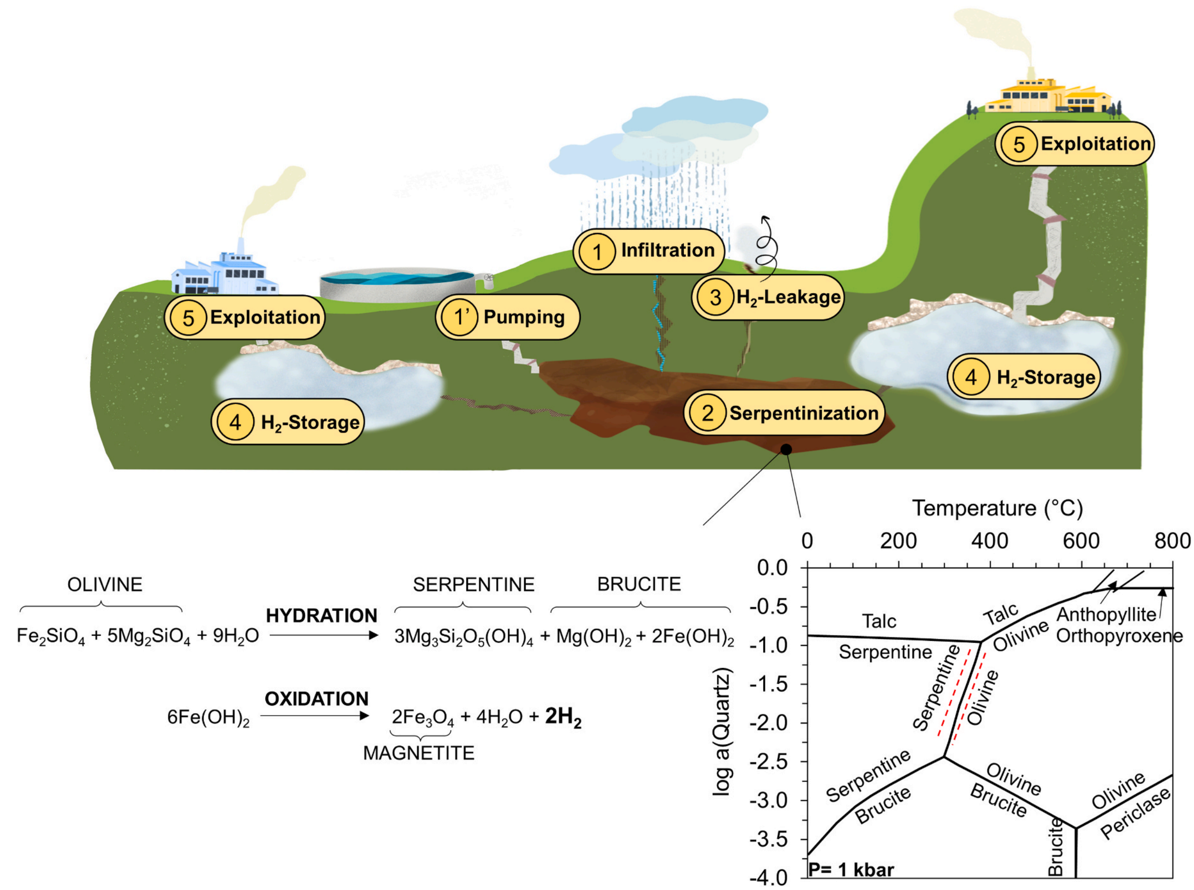

Fig. 3. Diagram of natural and orange hydrogen formation and exploitation, along with the key reactions involved in the serpentinization process (bottom left) and the phase diagram of quartz (bottom right. Temperature is represented along the x-axis and quartz activity along the y-axis) [21]. As water infiltrates through the crust, it can reach depths and rock compositions that are suitable for the process of serpentinization [1]. The rock bed undergoes hydration and oxidation during serpentinization, resulting in the production of natural hydrogen [2]. The hydrogen generated migrates towards the surface through fissures and cracks in the crust. It can then escape into the atmosphere [3] or become trapped by impermeable barriers, where it accumulates and forms deposits [4]. Some of these natural hydrogen deposits could be industrially exploited [10].

below this temperature range, the process occurs at very low rates, while at temperatures higher than 320–350 °C, olivine remains stable [23,28,29]. At higher pressure (3–20 kbar), the optimal temperature increased and the serpentinization rate increased up to 4 times [30]. The access of water to the rock, and therefore the water-to-rock mass ratio, also critically affects the serpentinization rate [21]. Water significantly affects the mobility of different metallic compounds and provides a suitable medium for these chemical processes. Additional parameters, such as the rock composition and impurities present in the reacting water, also play an important role in the reaction. For instance, the presence of aluminum has been shown to increase the serpentinization rate of olivine at 340 °C and 2 kbar [31]. Recently, Song and co-workers indicated that small amounts (<1 %) of nickel in the parent rock greatly enhance the rate of serpentinization reactions at low temperatures (<100 °C) [32]. Ultramafic rocks containing pyroxene in addition to olivine may serpentinize faster than monomineralic olivine: recent experiments with olivine-orthopyroxene powder (230 °C, 350 bar, water-to-rock mass ratio of 2) achieved a 53 % serpentinization in just 1 year of reaction [22].

Besides serpentinization, hydrogen can also be produced in the subsurface by other abiotic processes and by microbial metabolism [33]. Many microorganisms produce H_2 through fermentation and nitrogen fixation reactions in their metabolism (Fig. 2), which are leveraged for the design of hydrogen-producing bioreactors [34,35]. This type of microbial activities are also found in the subsurface [33,36]. Many identified microorganisms can only obtain energy through fermentation and they play an important role on the biogeochemical cycles in the deep subsurface [33,37]. Unfortunately, the importance of biological activity in the natural production of H_2 in the subsurface is not well understood. Recently, it has been shown that an important proportion of the H_2 detected in the subsurface of the Iberian Pyrite Belt is produced biologically [38]. Importantly, hydrogen may also be utilized as a source of energy by other microorganisms in the subsurface ecosystem. Studies of other mineral substrates and locations is needed to assess the extent of the biological contribution to natural H_2 formation.

3. Natural hydrogen hotspots

Estimating the amount of naturally occurring hydrogen that can be extracted or stimulated based on current data is challenging, although upper and lower bounds can be drawn. As an upper bound estimate, we can consider that, on average, peridotite can provide approximately 2–4 kg of H_2 per cubic meter upon oxidation. With an estimated 10^{12} Mt of peridotites in Earth's upper crust (top 7 km), there is a total of 10^8 Mt of hydrogen that could be theoretically generated from the subsurface [39]. To put this in perspective, such an amount would provide a supply of 1000 Mtpy of H_2 for 100,000 years [40]. As a lower bound estimate, Smith and colleagues estimated the potential hydrogen production from the Samail Ophiolite in Oman [41]. With a total volume of ultramafic rock around 125,000 km^3, of which only 50 % is serpentinized, it could provide approximately 260 Mt of hydrogen, exceeding the current world demand for one year [4]. Of course, these estimates relating the amount of rock to hydrogen production are very crude. However, they illustrate the latent potential that natural hydrogen could have. From another angle, combining data from various studies [2,12,42–45] it has been estimated that the natural hydrogen being formed on Earth could account for approximately 85 % of the current human-made production [12]. This estimate also has much uncertainty and it does not consider the hydrogen already formed and stored underground or the potential of stimulated H_2 production. It is also important to note that tectonic activity continuously refreshes rocks, with approximately 1000 Mt of peridotites being produced each year [39]. Therefore, these values might also underestimate the actual potential of natural hydrogen resources.

Although the exploitation of natural hydrogen is in its infancy, the numbers of boreholes, potential deposits discovered, and companies involved are increasing rapidly as observed in Fig. 4, where a detail of locations and some emergent companies is presented [12]. While numerous research projects worldwide are investigating natural hydrogen resources, detailed information about quantities, costs, and specific locations is often kept secret. Although many specific locations of interest are kept secret, several general areas with increased probability of hydrogen formation are known. In particular, underwater subduction zones, where water supply is constant and iron exposure is frequent due to plate movements, are coupled with natural hydrogen production [46]. Fossil oceanic spreading centers (ophiolites) and suture zones, representing complete subduction of an ocean basin where continents collided, are also promising targets for hydrogen prospecting [47,48]. On land, hydrogen seeps can often be identified by the creation of circular structures known as "fairy circles," which can serve as points of interest for natural hydrogen exploration (Fig. 4) [16,49].

One of the investigated fairy circles first is in Bourakébougou (Mali) and it has enabled uninterrupted hydrogen energy supply to the town since 2011. This natural reservoir has a diameter of more than 8 km. Prinzhofer and co-workers investigated this reservoir confirming the presence of up to five stacked layers of high-purity hydrogen on an old cratonic basement mainly composed of pyroxene, and proposed that its industrial exploitation could be cheaper than the cost of synthetic hydrogen [19]. In another fairy circle of 500 m diameter in Brazil, gas flows of up to 178,000 m^3 per day were estimated [17]. Differences in the release of H_2 during day and night were also detected, leading to the conclusion that there is a saturation mechanism of H_2 in the fairy circle that reaches its maximum desorption rate during the day [17]. Confirming the presence of deposits responsible for the release of this gas using seismic techniques could increase the interest in exploiting this location. In Chimaera (Turkey), uninterrupted hydrogen flows have been detected for over 2000 years [51]. In Aragón (Spain), the presence of a significant deposit of natural hydrogen beneath the Pyrenees mountain range has been confirmed [52]. Lefeuvre and colleagues studied a 10 × 10 km grid, taking and analyzing over 1000 *in situ* samples to identify different hydrogen hotspots in the region. Furthermore, they identified a saline formation that would have enabled the accumulation of this natural hydrogen. A company called Helios Aragon has been established to exploit this deposit, aiming for an annual extraction of $5.5 \cdot 10^4$ to $7 \cdot 10^4$ metric tons per year of pure hydrogen,

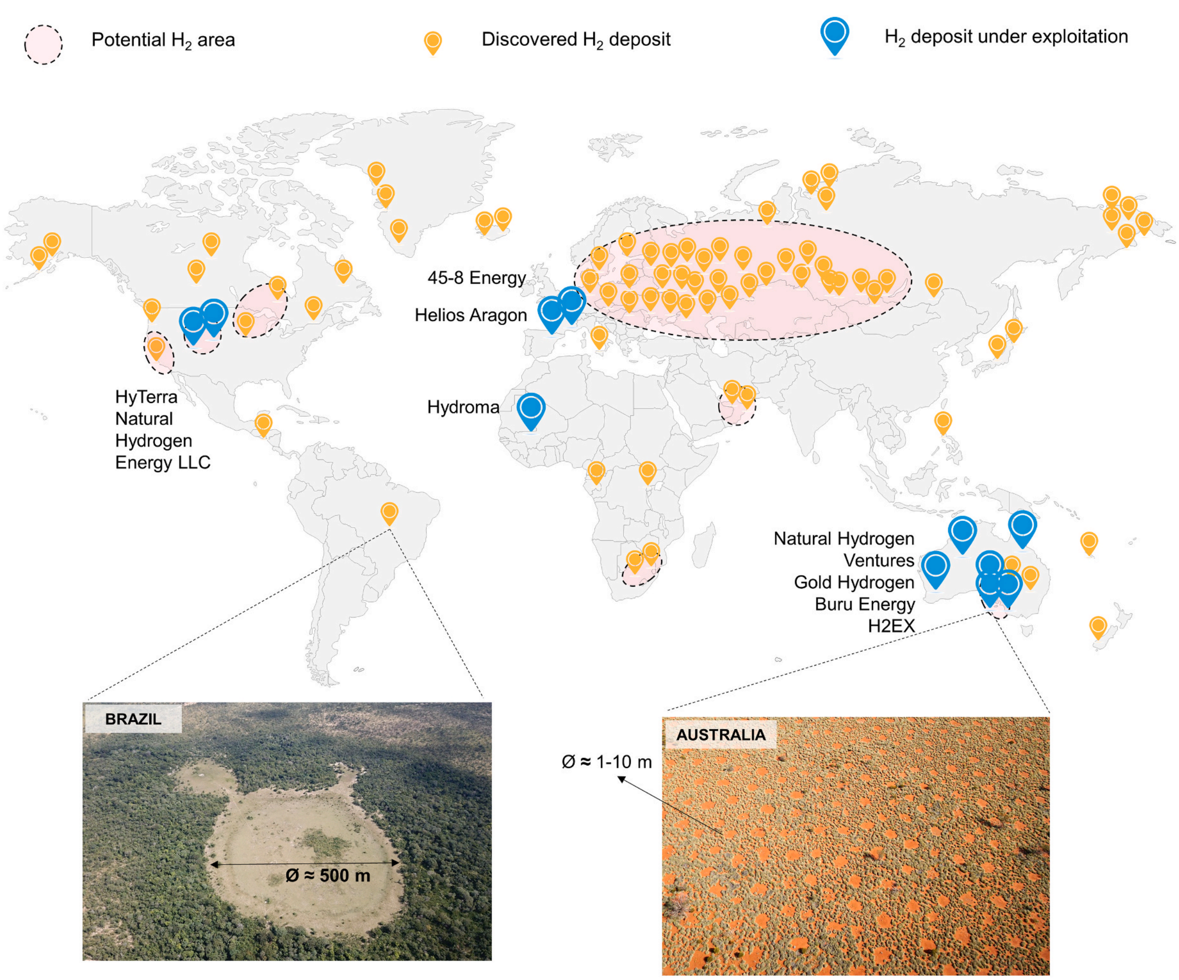

Fig. 4. Detail of known natural hydrogen deposits and fairy circles. Fairy circles can be found in regions around the world with diverse diameters, locations, and densities. Although the precise mechanism behind their formation remains enigmatic, they are often good indicators in the search for natural hydrogen [16]. Photos reproduced with permission from Refs. [17,50].

comparable to the production from a current steam methane reforming plant [11,53]. The company also anticipates a lower production cost for natural H_2 compared to other technologies. In Australia, over 40 licenses for exploring natural hydrogen deposits have been issued since 2021 [54]. One of these companies, Gold Hydrogen, has confirmed a deposit in southern Australia with an estimated extractable hydrogen quantity ranging from 1.3 to 8.8 Mt [55].

The initial localization of natural hydrogen deposits can be challenging. A major technique utilized to this end is seismic prospecting, which applies seismic waves to the ground and measures their reflection [56]. The time elapsed between the emission of the seismic wave and its reception at the detector, including reflections, provides an internal view of a few cubic kilometers underground. The generation of these waves is typically done with electric vibrators, which offer greater safety than traditional explosives. Nonetheless, seismic techniques frequently suffer from intrinsic noise produced by the measurement apparatus, leading to extended analysis periods aimed at extracting dependable information through noise reduction [57]. Furthermore, the interpretation and processing of these methods are intricate, demanding a profound mastery of the technique to extract meaningful insights. Companies like Xcalibur Multiphysics also deploy search techniques in airplanes capable of flying over hard-to-reach locations.

While seismic techniques can provide information on the dimensions of a gas reservoir, its exact composition must be confirmed through prospecting and chromatographic analysis [58]. Chromatographic analysis should be carried out using a carrier gas that allows the detection of hydrogen, such as He. Historically, however, chromatographic analysis of underground gases was often performed using H_2 as the carrier gas, which may have contributed to natural hydrogen deposits going undetected [12].

Estimating the amount of hydrogen contained in a reservoir requires combining seismic data with prospecting at different distances and depths from the initial analysis point. This allows triangulating the deposit's position and depth. Additional factors to consider in the exploitation of a natural hydrogen reservoir include its location, size, technical practicality, safety, composition, pressure, and the rate at which the reservoir may be naturally replenished. Monitoring the pressure evolution as gas is extracted also provides key information about the size and durability of the reservoir.

4. Exploitation of geological hydrogen

The extraction of natural hydrogen can be carried out by adapting technology currently employed for natural gas extraction [59]. Briefly, once the potential reservoir is confirmed by seismic techniques, a drilling rig is used to penetrate rock layers, while pipes are employed to facilitate the drilling. The continuous circulation of mud helps control the temperature and pressure throughout the drilling process. During this process, various issues can occur such as the loss of recirculated mud through infiltration into the rock, mud contamination, or pipe blockages. These problems can be minimized by selecting an appropriate drilling path and periodically checking the quality of the recirculated mud during drilling. Once the gas reservoir is reached, the pipes are lined with dense concrete to minimize gas migration and ensure structural integrity [55]. It is especially important to ensure the structural integrity of the installation by respecting the concrete drying times and operating with caution due to the reactive and diffusive nature of H_2. A H_2 leak at low depths can be dangerous due to the potential to form flammable and explosive mixtures with O_2. High-pressure valves are employed to control the extraction and maintain pressure within the reservoir. Once the pipes are in place, extracting hydrogen becomes relatively straightforward [59]. Extraction occurs through pipelines installed in the perforated rock, using the pressure of the pressurized hydrogen (usually >500 bar) to fill tanks for small-scale distribution.

Besides natural hydrogen, the production of orange hydrogen also has potential. However, there are currently no companies dedicated to this enhanced or stimulated extraction of hydrogen, making it difficult to provide details. To produce orange hydrogen, a suitable rock formation at an optimal reaction temperature would be required, which could be accessible to existing mining technology. Considering a geothermal gradient of approximately 30 °C/km, a formation with the right temperature for the process of 200–300 °C could potentially be found at depths between 5 and 10 km [60,61]. In this depth range, the lithostatic pressure would be around 2000 bar (assuming a typical formation density of 2750 kg/m^3). Drilling has reached depths up to 12 km, so a suitable formation could be accessible to current technology [62]. In addition to finding a suitable formation, it would be necessary to encounter an impermeable rock layer (e.g., halite) at shallower depths [63]. This layer would prevent hydrogen diffusion towards the surface. Once the rock formation were reached, water to stimulate the process would have to pumped at very high pressure. Although pumping water at great depth and pressure is not without challenges, much experience has been gained with the widespread of fracking technology in recent years, which could prove very useful for the stimulation of H_2. Once orange hydrogen were produced and accumulated, it may be possible to use extraction technology similar to that for natural hydrogen. An approach to the production of orange hydrogen can be observed in Fig. 3. The main difference with natural hydrogen lies in the pumping of water from a reservoir to the reactive bedrock.

Hydrogen possesses high molecular diffusivity, which makes large-scale storage of synthetic hydrogen a major challenge [64]. Cryogenic tanks and pipelines are used for small-scale distribution and immediate consumption. Alternatively, underground geological structures like salt caverns are being investigated as large-scale hydrogen storage facilities [65]. These are cavities formed by the dissolution of salt deposits in thick salt beds or domes deep underground [66]. They can provide secure and isolated storage environments, as the salt walls act as natural barriers against leakage [67]. Moreover, the plasticity of salt enables the caverns to withstand high pressures without collapsing, creating an ideal environment for hydrogen storage [63]. Efforts are underway to find suitable natural salt deposits, and countries like Poland are starting to develop an industry around this concept [68]. Overall, large-scale hydrogen storage is a subject of significant industrial interest. Since natural hydrogen is naturally stored in geological traps, the discovery of natural hydrogen deposits could not only provide the value of the hydrogen within it, but also the value of the reservoir itself.

One drawback of natural hydrogen can be its purity. Although deposits with very high purity have been found, impurities are frequently present [17,69], including gases such as nitrogen, methane, or unreacted CO_2, as well as moisture. The purity of natural hydrogen largely depends on the quality of the water that reached the reactive rock. Water often contains particles, carbonates, and CO_2 that can produce organic impurities through Fischer-Tropsch mechanisms, as the pressure, temperature, and composition of the rock favor such reactions [27,70–72]. Therefore, processing this gas may requires the use of desiccants (already used in all hydrogen stored in caverns due to similar impurities) and separation of light gases using membranes, cryogenic distillation, or pressure swing adsorption [73–75]. While separation costs could rapidly increase the production cost of natural hydrogen from some locations, certain impurities (e.g., CH_4) could also have market value. In the case of orange hydrogen, purity could be controlled by injecting water with controlled composition (as in electrolysis) to minimize potential contaminants and subsequent purification. However, purity requirements depend on the application. For example, if the goal is combustion for energy production, organic impurities along with moisture would pose a lesser problem [76].

Natural hydrogen can be transported in various forms, and the most cost-effective transportation option will depend on factors such as distance, scale, and intended use [77]. For long-distance transport of large quantities, pipelines become most cost-effective [78]. Small quantities, like those needed for refueling stations, are typically more efficiently transported by trucks. Liquefaction of hydrogen provides higher energy density compared to compressed hydrogen, but it comes with a higher production cost. Metal hydrides are another option for local storage of smaller quantities like those required in light vehicles. However, their main drawback is the production cost of suitable metal alloys and their increased weight [79,80]. Ammonia storage offers an even higher energy density than liquid hydrogen and can be stored at low pressure (1 bar) [81,82]. However, the drawback is that releasing hydrogen from ammonia by dehydrogenation requires significant energy. Hydrogenation and dehydrogenation of LOHCs (liquid organic hydrogen carriers) are less energy-intensive compared to ammonia, but the amount of hydrogen that can be extracted is lower [83,84]. These considerations highlight that the most cost-effective strategy depends on the specific application and context.

Overall, natural hydrogen offers significant potential to help decarbonize multiple sectors, including industries such as refineries, methanol production plants, and ammonia manufacturing facilities. Additionally, the transportation sector is poised for expansion through the development of new e-fuels and the adoption of ammonia as alternative fuels. Localized energy production using hydrogen presents an attractive option, and ongoing investigations into blending natural gas and hydrogen for heat supply demonstrate their compatibility with existing infrastructure [85]. Indeed, countries like UK already embrace some kind of hydrogen/natural gas blending strategy in their domestic gas heating system [86]. For industrial applications requiring high temperatures, such as steam crackers and cement kilns, hydrogen also emerges as a promising substitute for fossil fuels [87]. The integration of natural hydrogen into various sectors can thus accelerate the transition to a more sustainable and low-carbon economy.

5. Next steps for geological hydrogen

The industrial exploitation of natural hydrogen is still in its earliest stages, but it has the potential to become a significant source of hydrogen. Pioneering companies in the field of natural hydrogen exploitation offer a proof of principle. With its comparatively low production cost and carbon footprint, natural hydrogen holds great promise in supporting society throughout the energy transition. However, it is necessary to increase research efforts to evaluate the potential of this resource.

At this point, the authors envision two parallel lines of work for natural hydrogen and orange hydrogen. On the natural hydrogen side, continuing to search for more deposits and conducting in-depth evaluations of already discovered reservoirs, including techno-economic and life cycle assessment studies, will provide a more comprehensive understanding of this resource. To this end, bureaucratic and political support will be crucial in facilitating both the search and research. Otherwise, progress can be very slow and cumbersome past the laboratory scale. Countries like Australia, where legislation supports exploration and extraction, are experiencing the emergence of a novel economic sector around natural hydrogen.

Besides abiotic production, the significance of natural microbial H_2 production in the deep subsurface is currently unknown [38]. Active H_2 producing microorganisms isolated from the subsurface are currently under study to evaluate their biotechnological potential [88,37]. It would be of interest to evaluate their natural *in situ* subsurface activity as well, or the possibility of introducing them in underground locations with suitable geological substrates or pre-existing identified organic matter. An adequate phenotypic and genotypic characterization can teach us about their optimal operating conditions, and if the addition of required nutrients could stimulate their natural H_2 subsurface activity. The identification of subsurface H_2 production by microorganisms seems feasible in the mid-term, but the quantitative evaluation of their performance will need an important investment and should be considered a longer-term endeavor.

Studies on the natural and stimulated regeneration of the reactive bed should also be conducted to ensure sustainable, long-term exploitation of geological hydrogen. For instance, leveraging microorganisms that utilize Fe^{3+} as their final electron acceptor in metabolism could be an interesting research direction to accelerate rock regeneration by replenishing Fe^{2+} (e.g., adapting the Feammox process) where other nutrients are available [89–93]. Additionally, the incorporation of different molecules into the pumped water to couple different reactions with serpentinization could be interesting. For example, the incorporation of dissolved CO_2 in the water to form solid carbonates during the serpentinization process, could enable the capture of CO_2 while producing H_2. On the orange hydrogen side, there are even more challenges and unknowns to investigate before it can be exploited at the industrial scale. Here, the study of serpentinization reactions in laboratories could provide essential knowledge. In Section 2, the challenge of controlling this reaction, which has seen limited laboratory research, has been emphasized.

In our opinion, the data available to date offers compelling evidence for the availability of a much-needed alternative energy source as society transitions beyond fossil resources. However, in-depth research is necessary to ascertain the durability of natural hydrogen reserves. As learned from the exploitation of fossil fuels, all deposits are finite. Therefore, as we start to exploit natural hydrogen resources safely, efficiently, and equitably, we should also invest research efforts in stimulation and in biotechnological solutions that could further improve the accessibility and sustainability of geological resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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