

Briefing 50

Native hydrogen

July 2026

National Assembly (17th leg.) no. 3011 – Senate no. 849 (2025-2026)



Witch's circles in Brazil corresponding to hydrogen emissions
Credit: Isabelle Moretti

Summary

- Natural hydrogen is produced and accumulates underground. There has recently been a surge in studies reporting potential natural hydrogen deposits around the world, raising hopes that 'white' hydrogen could make a significant contribution to a net-zero carbon future.
- Nevertheless, no large-scale, economically viable deposits have been discovered to date. The actual costs of extracting natural hydrogen have yet to be assessed, particularly in view of the specific characteristics of each site.
- To address these uncertainties, it is essential to fund fundamental research into geological hydrogen systems and, subject to appropriate conditions, provide public support for exploratory drilling in advanced French projects.

Gérard Leseul, Member of the National Assembly

Michaël Weber, Senator

■ The formation of natural hydrogen: a phenomenon widely documented worldwide

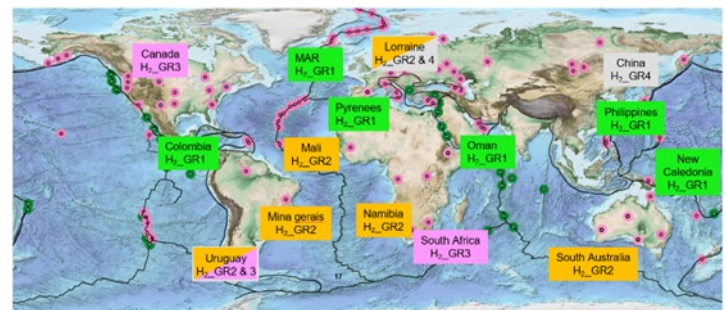
- A potential resource distributed across numerous geographical areas

Natural hydrogen¹ occurs as molecular hydrogen (H_2) and is not combined with any other element. It is present in the Earth's atmosphere at very low concentrations and, at slightly higher concentrations, in dissolved form in water (H_2O). Hydrogen also occurs naturally in gaseous form within porous rocks underground, where it is generally mixed with other gases such as nitrogen (N_2), helium (He) and methane (CH_4)², or dissolved in groundwater.

The first global³ survey of hydrogen seepage, carried out in 2020, detected measurable physical indicators on every continent. In 2023, this study was followed by a further assessment of areas where potential hydrogen-generating rocks are present⁴.

In mainland France, the Aquitaine Basin, the Pyrenean Piedmont and the Grand Est region appear to offer favourable conditions for the occurrence of hydrogen. In the overseas territories, the ophiolitic massifs of New Caledonia and French Guiana possess the geological characteristics conducive to the presence of natural hydrogen. However, no exploratory studies have been carried out to date in French Guiana.

Global distribution of rocks with hydrogen-generating potential



Source: Isabelle Moretti, 2026, based on Levy et al. (2023)

H2_GR1: basic and ultramafic rocks / mantle rocks

H2_GR2: iron-rich rocks (sedimentary or intrusive)

H2_GR3: radioactive continental rocks

H2_GR4: rocks rich in organic matter

- The geochemical mechanisms of natural hydrogen production

Several mechanisms contribute to natural hydrogen production, but only three of them are likely to result in economically viable accumulations of natural hydrogen.

• Redox reactions

Redox reactions between water and certain iron-rich rocks involve oxidation of the rocks and conversion of water into dihydrogen under specific hydrodynamic conditions⁵.

The process is based on an exchange of electrons between the two elements:

- on contact with water, the ferrous iron contained in the rock (Fe^{2+}) acts as a reducing agent: it donates electrons and is converted into ferric iron (Fe^{3+});
- by capturing the electrons released by iron in the rock, the hydrogen in water (H_2O) is reduced to form gaseous dihydrogen (H_2).

Serpentinisation is the best-known process involving the hydration⁶ and oxidation⁷ of ultramafic⁸ and mafic⁹ rocks containing olivine and pyroxene. Other rock formations, such as granites and banded iron formations¹⁰, can produce hydrogen through redox reactions. The reaction kinetics are most favourable at high temperatures (between 200 and 350°C), but serpentinisation may continue at temperatures below 50°C under certain conditions¹¹.

- *Radiolysis of water*

Radiolysis of water is another reaction that produces natural hydrogen on a large scale. It involves the breaking of O–H bonds in water by ionising radiation produced during the radioactive decay of uranium, thorium and potassium. Helium is also produced during this reaction. Radiolysis occurs in all radioactive continental rocks. The process can take several billion years¹².

- *The maturation of organic matter*

When carbon-rich sediments are buried deep underground, the rise in temperature causes the thermal cracking of organic molecules. At very high temperatures (the overmaturation stage), hydrocarbon chains break down, releasing methane and significant quantities of dihydrogen. Rocks rich in organic matter include coal and black shales. The rate of organic matter maturation depends on temperature, but it can take hundreds of millions of years¹³.

- *Other processes*

Volcanic degassing¹⁴, mechanoradical reactions¹⁵ and microbial activity¹⁶ can also generate natural hydrogen.

➤ *The start of exploration activities*

Over the past five years, the number of publications on natural hydrogen has increased twentyfold, and numerous companies¹⁷—mainly start-ups—have begun exploring natural hydrogen. Although exploration of natural hydrogen only began in France in 2022, the country benefits from a scientific head start built on more than a decade of research programmes, as well as a hydrogen and ‘para-hydrogen’ sector structured around the AVENIA competitiveness cluster as part of the European Earth₂ initiative on native hydrogen¹⁸. Internationally, hydrogen exploration projects are underway on every continent at varying stages of progress¹⁹. However, only a limited number of countries²⁰ have adapted their legislation to issue natural hydrogen exploration licences.

➤ *The reality on the ground: data remains scarce and there is only one production site*

- *The lack of publicly available scientific data on recent drilling*

Outside Mali, between 20 and 40 wells²¹ have been drilled across all continents, particularly in the United States and Australia, but also in Colombia, China and even France²². However, to date, these operations have not resulted in the publication of any verified data or peer-reviewed results in scientific journals²³.

- *The case of Mali*

There is currently only one site in operation in the world: the Bourakébougou site in the Taoudeni Basin in Mali²⁴. There, hydrogen occurs as free gas at shallow depth. It is produced in a near-pure form (approximately 98 per cent). However, the flow rate from the original main well²⁵ is only 1,500 m³ per day, or 48 tonnes per year—the equivalent of the energy contained in 3 barrels of oil—compared with 2 million m³ per day of natural gas from a North Sea well. By comparison, a typical fertiliser plant uses an average of 300,000 tonnes of hydrogen per year.

■ **Understanding natural hydrogen systems: a prerequisite for planning natural hydrogen exploitation**

Natural hydrogen resources encompass all quantities of natural hydrogen present in the Earth’s crust, whether discovered or not, and whether recoverable or not.

Hydrogen seeps, springs and subcircular depressions provide valuable insights into hydrogen fluxes, but do not allow for the assessment of resources.

The absence of any hydrogen signal may constitute a false negative²⁶: the measuring instruments detect hydrogen leaks rather than the presence of the gas in the subsurface.

Surface phenomena can also cause false positives due to surface microbial activity²⁷ or chemical reactions during drilling²⁸.

Hydrogen deposits result from a ‘hydrogen system’, i.e. a comprehensive geological model encompassing all the physical and chemical elements and processes necessary for the generation, migration, trapping and retention of hydrogen in the subsurface. Understanding this system is essential for assessing hydrogen resources.

➤ *The key components of the ‘hydrogen system’*

The concept of the ‘hydrogen system’ is directly based on the ‘petroleum system’ model, while taking into account the properties of the hydrogen molecule. For a hydrogen system to function, four elements must be present: the source, the migration pathways, the reservoir and the caprock.

- *The source: hydrogen-generating rocks*

There are several types of rock capable of producing hydrogen. To generate hydrogen through redox reactions and radiolysis, source rocks must have a favourable chemical composition (high ferrous iron content or high concentration of radioactive elements) as well as a network of microfractures allowing water to infiltrate and continuously sustain the hydrogen-generating reaction.

- *Migration pathways*²⁹

Compared to hydrocarbons, hydrogen is a very small molecule. Once formed, the hydrogen migrates out of the source rock via two mechanisms³⁰:

- by advection: hydrogen is transported either dissolved in water (in which case it follows the aquifers) or as a free gas. Advection transports hydrogen along targeted permeable pathways such as fractures, faults or porous layers;
- by diffusion: hydrogen molecules move spontaneously down a concentration gradient³¹ in multiple directions.

At great depths, under hydrostatic pressure, hydrogen migrates dissolved in water along aquifers. At shallower depths, as the pressure decreases, hydrogen is released as a gas, thereby forming gas accumulations or escaping into the atmosphere³².

- *The reservoir rock*

As hydrogen is a highly mobile gas, the reservoir rock must have high porosity to provide pore space for the gas, and sufficient permeability to allow fluid flow³³. Typical reservoir rocks include porous sandstones and fractured rocks such as carbonates or crystalline source rocks with well-developed fracture networks³⁴.

- *The caprock*

The amount of natural hydrogen that can potentially be extracted depends largely on its ability to accumulate in geological traps³⁵. Without an impermeable layer above the reservoir rock, the hydrogen escapes to the surface. Based on current knowledge, the most suitable caprocks are salt³⁶ and certain water-saturated clays³⁷.

When hydrogen is dissolved in an aquifer, a trap is probably not required.

➤ *Numerous uncertainties exist*

- *Formation and migration*

The rate of hydrogen-producing reactions varies depending on temperature, pressure, the water-to-rock ratio³⁸, the salinity of the fluid³⁹, and the chemical composition of the rocks and fluids. Little is known about natural catalysts, while the serpentinisation of olivine⁴⁰ – a key process for hydrogen production – is accompanied by other geochemical reactions that may hinder hydrogen production.

The precipitation of secondary minerals⁴¹ can lead to surface passivation: by depositing uniformly on the walls of microfractures, they form an impermeable barrier and isolate the core of the rock from any future contact with water. Hydrogen production comes to an abrupt halt, leaving an iron-rich rock that is no longer capable of producing hydrogen.

The effects of these coupled reactions remain particularly difficult to model due to their complexity (antagonism between certain reactions⁴², variable kinetics and yields⁴³, etc.).

Rocks with high hydrogen potential (peridotites) are characterised by low porosity and low permeability. However, most peridotites and other potential hydrogen source rocks observed on the Earth's surface are heavily weathered, indicating efficient fluid circulation mechanisms⁴⁴.

These mechanisms remain poorly studied, limiting our ability to predict the hydrogen production potential of areas considered favourable for hydrogen exploration.

- *Accumulation and preservation*

The accumulation of hydrogen is hampered by its exceptionally high diffusivity, which causes it to leak towards the surface through the overlying rock. Although diffusion is a slow process, over geological timescales it could be sufficient to deplete a reservoir that is not continuously replenished.

Another obstacle to hydrogen storage is its chemical and microbiological reactivity. Hydrogen has moderate electronegativity and a small atomic size, which facilitates electron transfer or the formation of bonds with other elements. Geochemical reactions involving hydrogen can occur at temperatures above 200°C: reduction of metal oxides (iron or manganese oxide) and oxidation of hydrogen to water; reduction of CO₂ to form methane⁴⁵; and reduction of sulphates to produce hydrogen sulphide⁴⁶.

At temperatures below 100°C⁴⁷, hydrogen is a source of energy for living organisms, and underground microorganisms play a major role in the consumption and transformation of hydrogen⁴⁸. Consequently, hydrogen traps are thought to occur at depths where the temperatures range between 100 and 200°C⁴⁹, where hydrogen is less reactive.

■ *The commercial exploitation of hydrogen: key factors and challenges*

The term 'resources' refers to the stock of hydrogen available in the natural environment; 'reserves', meanwhile, refers to the quantities of hydrogen that could be extracted in a commercially viable manner.

Companies exploring for natural hydrogen are aiming for production costs of around one dollar per kilogramme of hydrogen⁵⁰. Assessments based on data from the Bourakébougou deposit⁵¹ or hypothetical deposits⁵² indicate production costs that are significantly lower than those of green hydrogen⁵³ and broadly comparable to, or even lower than, those of grey⁵⁴ and black⁵⁵ hydrogen. Nevertheless, to date, the actual cost of producing natural hydrogen has yet to be determined, as it has never been produced or marketed on a large scale⁵⁶. Numerous factors can influence production costs.

➤ *Technical and logistical factors affecting economic viability*

- *Dissolved hydrogen or free gas: the bottleneck in extraction*

The methods envisaged to extract hydrogen as a free gas are those traditionally used to exploit pressurised hydrocarbon reservoirs. By contrast, the extraction of hydrogen dissolved in water poses numerous technological challenges⁵⁷.

- *Purity and potential co-products*

The hydrogen concentration and the composition of the residual gas are key factors in determining profitability⁵⁸ as they define the energy requirements and gas separation costs⁵⁹ for hydrogen purification.

The presence of helium, however, can make hydrogen deposits profitable due to the high market value of this gas⁶⁰. Helium is a rare gas that is essential in many industrial sectors, while supply is limited by the number of exploitable deposits.

- *Flow rate and pressure*

High production flow rates lead to lower unit costs through economies of scale. The flow rate required for commercial viability is estimated at several kilotonnes per year per well⁶¹. Reservoir pressure directly influences the rate of hydrogen production: high pressure facilitates extraction and improves the overall efficiency of the production process.

- *Total volume and depth*

The total quantity of hydrogen present in the reservoir determines how long a given flow rate can be maintained. In the field of gas exploration, the operational lifespan of a production facility typically ranges from 15 to 30 years.

The depth of the reservoir is an important factor in drilling costs: the deeper the reservoir, the higher the drilling costs⁶².

- *Proximity to consumers*

Because transporting hydrogen is technically complex and costly⁶³, it is more likely to be economically viable when consumers are located close to the reservoir.

➤ *Regulatory, financial and cultural barriers in France*

- *Lengthy and costly procedures*

The exploration phase begins with the granting of an exclusive exploration licence, a process that takes longer than in other countries (18 months in France compared with 3 to 6 months in Germany). Two reasons are regularly cited: sequential rather than parallel authorisation procedures; and a shortage of staff with expertise in subsurface matters to process applications, even as these applications become increasingly complex. Applications for production concessions are said to take even longer, with processing times of up to three years.

Furthermore, the Mining Code does not facilitate access to pre-existing data. For example, seismic data is only available in a format that requires reprocessing before it can be used, resulting in additional costs and delays⁶⁴.

- *The high cost of drilling*

Drilling remains the only way to confirm the existence of an underground hydrogen deposit, to measure the pressure, flow rates and composition of the gas, and to assess economic viability. However, it is expensive, costing between €2 million and €20 million, posing a real challenge for exploration companies, most of which are start-ups.

- *Declining interest in France's subsurface resources*

Subsurface resources are set to play a vital role in the energy transition, and in France's energy sovereignty. However, they remain little known to the general public, and their exploitation is hindered by limited public acceptance and a relative lack of interest among policy-makers.

■ Recommendations

- Develop a narrative around France's subsurface resources to raise awareness among policy-makers and the public of their strategic importance and France's potential
- Allocate €10 million to a 10-year national multidisciplinary research programme on hydrogen and helium, culminating in the drilling of one or two deep boreholes to characterise the systems associated with these resources
- Secure France's contribution to the two international scientific drilling programmes (International Continental Scientific Drilling Programme and International Ocean Drilling Programme) in order to maintain French expertise in understanding the subsoil
- Establish a fund of €10 million in repayable advances to support the drilling of an exploratory borehole for the most advanced French projects, provided they are accompanied by an associated public scientific programme
- Amend mining legislation to allow free access to reprocessed seismic data and simplify the processes for granting exploration permits and production licences
- In the context of international competition in the energy sector, support the recognition of natural hydrogen as a low-carbon energy source at European level by revising the European Union's hydrogen strategy from 2027 onwards

The Office's websites:

<http://www.assemblee-nationale.fr/commissions/opecst-index.asp>

<http://www.senat.fr/opecst>

People consulted

People interviewed

- *IFP Energies nouvelles (IFPEN)*
 - *Ms Julie Lhomme Maublanc, Director of Information and Institutional and International Relations*
 - *Mr Yannick Peysson, R&D Programme Manager for Natural Hydrogen*
- *Ms Isabelle Martinez, professor at the Paris Institute of Earth Physics (IPGP)*
- *Bureau de Recherches Géologiques et Minières (BRGM)*
 - *Mr Frédéric Gal, Research Engineer*
 - *Mr Frédéric Glanois, Director of the Energy and Decarbonisation Division*
 - *Mr Francis Claret, Head of the Energy Programme*
- *Directorate-General for Energy and Climate (DGEC)*
 - *Mr Fabrice Candia, Head of the Underground Energy Resources Office*
 - *Mr Jean-Claude Lecomte, Geoscience Sector Expert*
 - *Mr Alexandre Chevallier, Deputy Director for Security of Supply, Energy and Mineral Resources*
- *Ms Isabelle Moretti, Researcher at E2S UPPA and Sorbonne University, Member of the French Academy of Technologies (Vice-President of the Energy Division)*
- *Mr Viacheslav Zgonnik, CEO of Hyrevel*
- *Mr Sébastien Lacaze, CEO of Look Up*
- *Mr Christophe Rigollet, Director of Geoscience at CVA*
- *Vinci Technologies*
 - *Mr Nicolas Bouton, Head of the Rock-Eval Department at Vinci Technologies*
- *Avenia – Earth2 programme*
 - *Mr Nicolas Gonthier, Head of the Earth 2 programme*
 - *Mr Christophe Hecker, Head of External Relations*
- *Storengy SAS*
 - *Mr Alain Caracatzanis, Managing Director*
 - *Ms Delphine Patriarche, R&D Manager*
 - *Mr Olivier Lhote, Director of Hydrogen Projects*
 - *Ms Océane Peylachon, Parliamentary Affairs Officer, Engie SA*
- *Mr Emmanuel Masini, Chairman and CEO of Mantle 8*
- *Mr Gaëtan Bonhomme, Chief Executive Officer of Breakthrough Energy Ventures Europe*
- *Mr Laurent Truche, Professor at the University of Grenoble Alpes (UGA)*
- *Air Liquide*
 - *Ms Nathalie Schmitt, Director of Public Affairs for the Energy Transition*
 - *Mr Simon Jallais, R&D Engineer*
 - *Mr Pierre Cavelan, Director of Corporate Public Affairs*
- *Ms Marguerite Godard, CNRS Research Director, Géosciences Montpellier*
- *Vermilion Energy France*
 - *Ms Pantxika Etcheverry, Managing Director*
 - *Ms Marine Di Matteo, Project Manager*
 - *Mr Thomas Chauvet, Head of Permits and Environment*

Visit to the Pontpierre site and 45-8 Energy (7 May 2026)

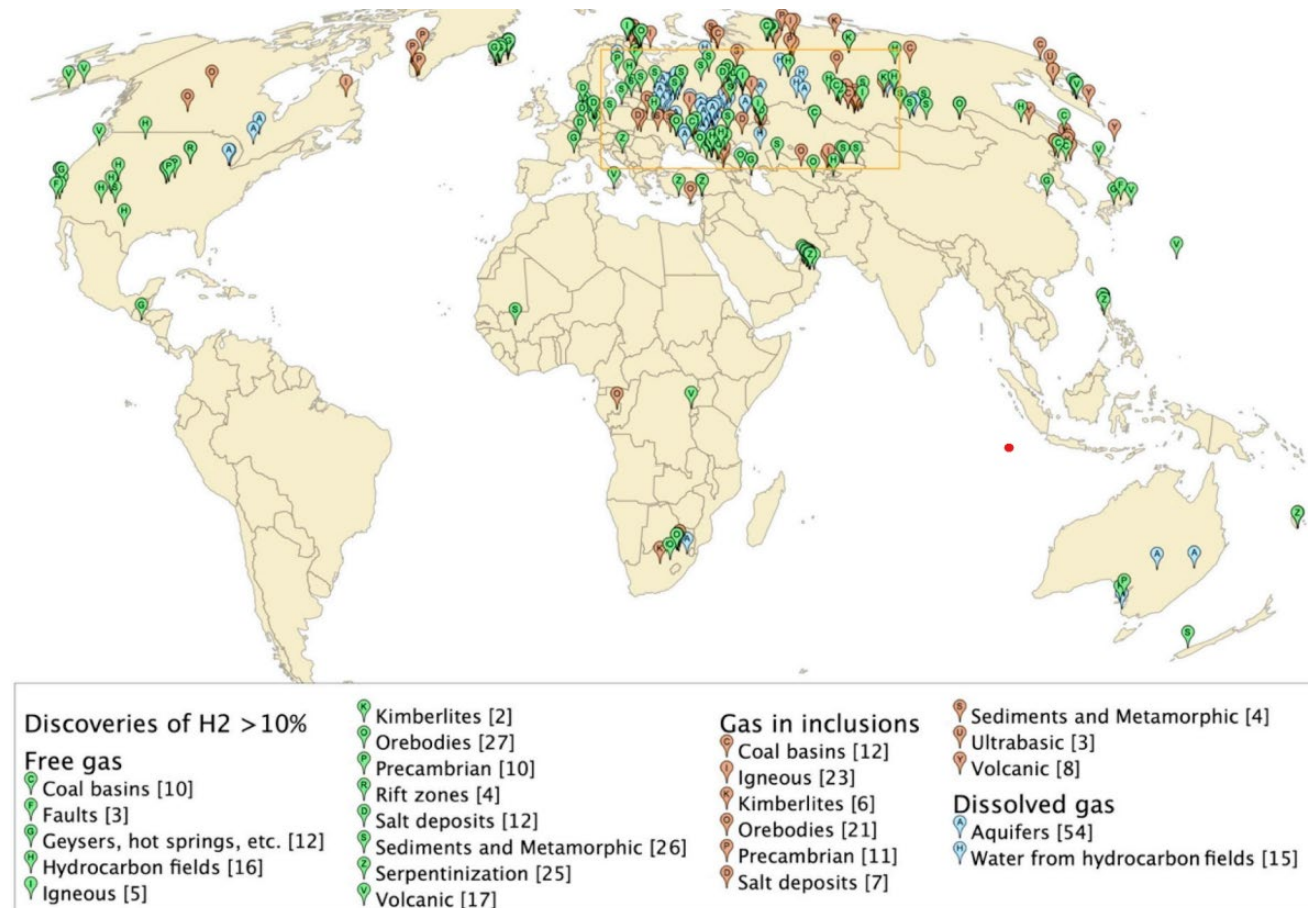
- *Mr Jacques Pironon, Emeritus Research Director at the CNRS*
- *Mr Antoine Forcival, Deputy Managing Director of La Française de l'Énergie*
- *Mr Nicolas Pélissier, Chairman of 45-8 Energy*

¹ It is also known as 'native', 'white' or 'gold' hydrogen.

² However, it has also been found in a near-pure form in the Bourakébougou deposit in Mali, for example.

³ Viacheslav Zgonnik. "The occurrence and geoscience of natural hydrogen: A comprehensive review." *Earth-Science Reviews* 203, 2020.

Map showing hydrogen detections in various environments where concentrations exceed 10% by volume.



By summing the estimated fluxes for each geological context, this article estimated total hydrogen production of 23 million tonnes per year.

It should be noted that the high density of data points in Eastern Europe and Northern Asia reflects the greater volume of research conducted in these regions, rather than a higher abundance of hydrogen.

In 2025, a new assessment of hydrogen fluxes was carried out (see *The Royal Society. Natural Hydrogen: future energy and resources. Policy briefing*, June 2025). It estimates that hydrogen production in the oceanic crust is unlikely to create an environment conducive to the accumulation of commercially exploitable free-gas deposits. Consequently, the assessment focused on potential flows from continental systems, where commercial exploitation would be more feasible. Three contexts were identified:

- continental volcanic zones;
- Precambrian continental crust;
- ophiolitic complexes.

Including volcanic gas fluxes, the total continental geological hydrogen flux is estimated to be less than 1.74 million tonnes per year. Excluding volcanic gas fluxes, which are considered unlikely to constitute a commercially viable target, the continental hydrogen flux is estimated to be less than 0.74 million tonnes per year. Nevertheless, this remains a substantial figure, particularly if hydrogen fluxes accumulate in underground traps over long geological timescales.

⁴ Levy *et al.* "Natural H₂ exploration: Tools and workflows to characterise a play." *Science and Technology for Energy Transition*, 2023, 78.

⁵ This reaction produces dihydrogen solely because the water has a low O₂ content. It can therefore only take place in a confined environment, without direct contact with the Earth's atmosphere, or in an aquifer in equilibrium with the atmosphere (there is no net gas flow between the aquifer and the atmosphere).

⁶ In the hydration reaction, there is no exchange of electrons. A chemical substance incorporates water molecules (H₂O) or hydroxyl groups (OH⁻) into its structure. In the case of the serpentinisation of olivine, water is incorporated into the olivine to form a new water-bearing mineral: serpentine.

⁷ The iron (Fe^{2+}) contained in olivine donates its electrons to the hydrogen in the water. The iron is oxidised to form magnetite and the hydrogen is reduced and released as hydrogen gas (H_2).

⁸ These are rocks that contain very little silica (less than 45 per cent) but are extremely rich in iron and magnesium, much like peridotite (a rock found in the Earth's mantle).

⁹ These are rocks with a moderate silica content (45–52 per cent), rich in iron, magnesium and calcium, such as the basalt found in the oceanic crust.

¹⁰ Certain minerals found in granites can weather to produce hydrogen, including biotite, iron-rich amphibole and fayalite. Banded iron formations (BIFs) are rich in siderite and magnetite, which can weather when exposed to infiltrating surface rainwater, producing hydrogen and creating circular structures known as 'witch's circles' in which gas seepages locally kill vegetation

¹¹ Ellison *et al.* "Low-temperature hydrogen formation during aqueous alteration of serpentinised peridotite in the Samail ophiolite." *Journal of Geophysical Research: Solid Earth*, June 2021, 126 (6).

¹² Hydrogen production rates are of the order of $\mu\text{mol/kg rock/Ma}$ (millions of years). This reaction has been ongoing since the Earth's formation more than 4 billion years ago.

¹³ Sediments rich in organic matter must be buried (a process known as subsidence). The temperature of 200°C at which the organic matter matures is reached at a depth of approximately 8 km. It is the subsidence of the sedimentary basins, rather than the reaction itself, that takes time. Hydrogen production rates are of the order of mmol/kg rock/Ma .

¹⁴ Volcanic activity releases gases, including hydrogen, from the magma.

¹⁵ Mechanical stresses (friction, fractures, pressure) within rocks can break Si–O bonds (in silicate minerals), creating free radicals. In the presence of water, these free radicals recombine and generate hydrogen as a by-product.

¹⁶ Biological hydrogen production relies on the metabolism of certain microorganisms capable of breaking down organic matter or using inorganic substrates to produce hydrogen. The most common production mechanisms are anaerobic fermentation, photofermentation, sulphate or sulphur reduction, and hydrogen production through the action of the enzyme nitrogenase.

¹⁷ Académie des technologies. *Accelerating the characterisation of resources and the exploration of natural hydrogen in France*. Opinion approved by the Assembly on 12 June 2024.

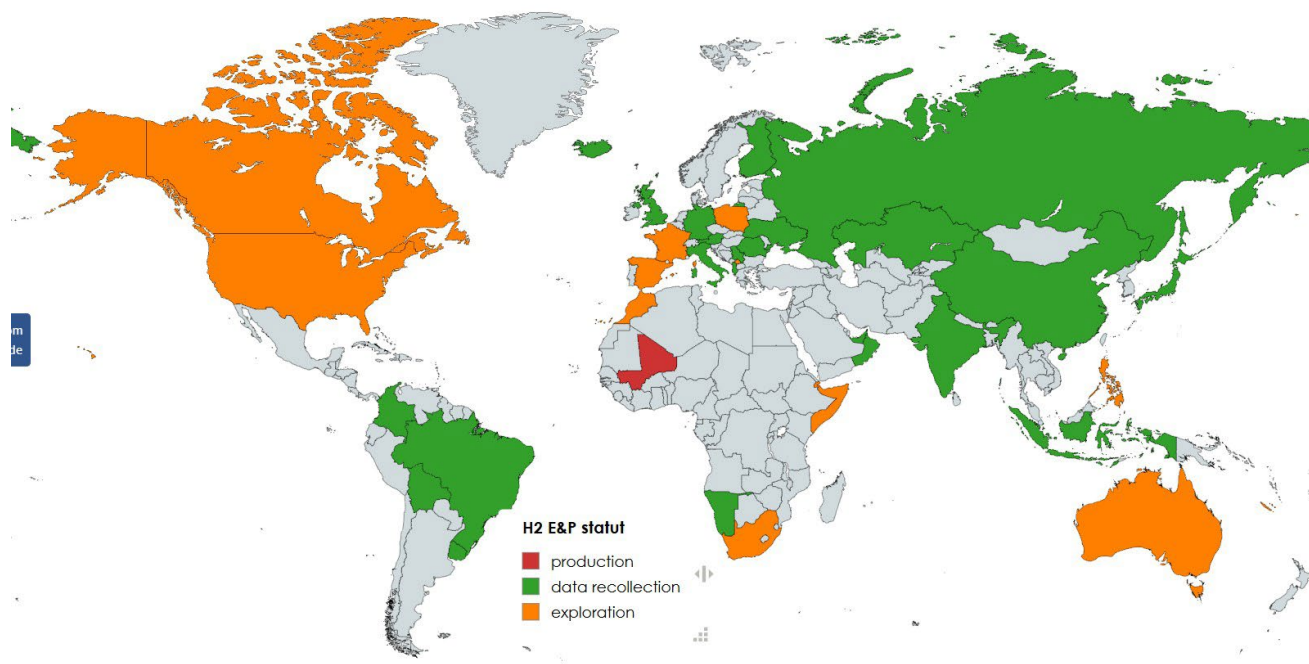
Mapping global stakeholders



¹⁸ Earth2 brings together around forty members representing a wide variety of sectors, reflecting the cross-cutting nature of the natural hydrogen sector (including companies specialising in exploration and mining, service providers, equipment manufacturers, research centres, regional representatives, public agencies and central government, as well as private and institutional investors).

¹⁹ Isabelle Moretti. Update of the map 'Overview of global prospecting, exploration and production of natural hydrogen' from the *Hydrogen Technology Collaboration Programme* report, *Natural hydrogen*. Chapter C. Authors: Isabelle Moretti, Emanuelle Frery, Humberto Reis, Carmen Font and Thomas Sandison. 14 March 2024.

Overview of global natural hydrogen prospecting, exploration and production



²⁰ These countries include the United States, Australia, Russia, Canada, China, Norway, Mali, Oman, Morocco, the Philippines, as well as several European Union countries (France, Spain, Germany, Austria, Italy and Poland).

²¹ Interview with Viacheslav Zgonnik. 27 May 2026.

²² Six exclusive exploration licences for native hydrogen have been awarded to date: to TBH2 in Sauveterre (Pyrénées-Atlantiques) on 23 November 2023; to the 45-8/STO consortium in Grand Rieu (Pyrénées-Atlantiques) and Marensin (Landes) on 25 February 2025; to TBH2 in Coucourou (Pyrénées-Atlantiques) on 22 December 2025; to La Française de l'Énergie in Les Trois Évêchés on 26 January 2026 (Meurthe-et-Moselle/Moselle); and to the G&OI/Mantle 8 consortium in Comminges (Haute-Garonne/Hautes-Pyrénées) on 31 March 2026. As part of the REGALOR 2 research programme, a well was drilled to a depth of 3,662 metres at Pontpierre, Moselle, on 16 March 2026.

²³ In 2023 and 2024, Gold Hydrogen carried out two drilling campaigns on the York Peninsula in Australia around a well where natural hydrogen had previously been discovered in 1931 with a purity of 90 per cent. According to information published by the company, the Ramsay 1 and Ramsay 2 boreholes reportedly revealed very high concentrations of hydrogen, corrected for the effect of air (73 per cent and 86 per cent respectively). Concentrations of helium of up to 6.8 per cent were also reported. However, no information was provided on the volumes of hydrogen or helium present, nor on the expected flow rates. <https://www.goldhydrogen.com.au/wp/wp-content/uploads/2023.12.19-ASX-Announcement-Very-High-Concentrations-of-Hydrogen-Found-at-Ramsay-2.pdf>

Following the drilling carried out by La Française de l'Énergie in March 2026 at Pontpierre, a figure of 34 million tonnes was put forward to quantify the dissolved hydrogen resources in the Lorraine basin. However, this assessment has yet to be confirmed and no information on expected flow rates has yet been published. According to La Française de l'Énergie, a scientific article is currently under review by the *International Journal of Hydrogen Energy* and is expected to be published once validated.

The only scientific data obtained following drilling come from the scientific drilling operations carried out in Oman (OmanDP) and on the Mid-Atlantic Ridge (IODP Expedition 399).

²⁴ This natural hydrogen deposit was discovered by chance in 1987 during a water drilling programme. It has been in operation since 2012 and powers a small power station that supplies the village with electricity.

²⁵ A further 24 wells have been drilled by Hydroma Inc. However, the individual flow rates have not been made public.

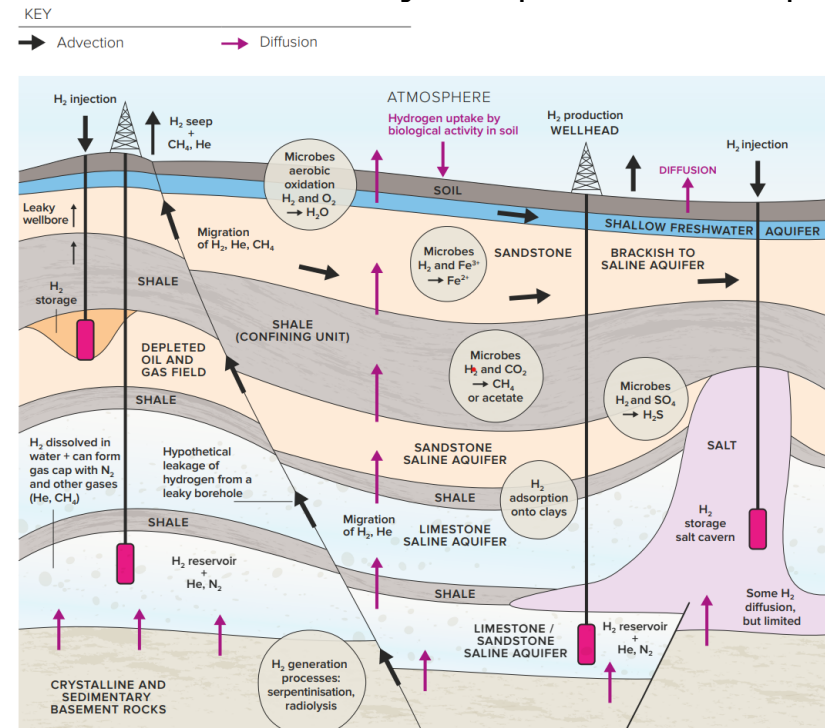
²⁶ This is the case, for example, when the rate at which the hydrogen rises is slow and soil bacteria consume the entire gas flow before it reaches the exploration team's sensors.

²⁷ Soils harbour microorganisms capable of producing hydrogen. Pockets of gas detected very close to the surface may reflect this biological activity (fermentation) rather than upward migration of hydrogen from a geological reservoir.

²⁸ During drilling operations, the interaction between drilling fluids, metal tools and certain rocks can generate hydrogen artificially.

²⁹ The Royal Society (June 2025). Study cited above.

Schematic cross-section showing the transport of hydrogen from deep reservoirs to near-surface environments, including shallow aquifers, soils and the atmosphere



The upward arrows indicate the natural release of hydrogen (and co-emitted gases) via seeps, springs and soils. The downward arrows above the soil indicate the uptake of hydrogen by biological activity in the soil.

³⁰ The Royal Society (June 2025). Study cited above.

³¹ Hydrogen has unique physical properties that promote its diffusion:

- hydrogen always moves from areas of high concentration (deep rock where it is generated) to areas of low concentration, such as the surface and the atmosphere (Fick's law);
- hydrogen is the smallest and lightest of all molecules. Consequently, its diffusion coefficient is extremely high, approximately three to four times greater than that of methane;
- due to its microscopic size, hydrogen does not merely diffuse through water or gases contained within rock pores. It can also seep through the solid crystalline structure of minerals or rocks considered to be impermeable.

³² Berit Erlach *et al.* *Geological Hydrogen – An Overlooked Energy Source?* Impuls, April 2026.

³³ High permeability allows water or carrier gases to flow freely. It is this permeability that enables hydrogen to migrate rapidly from deep source rocks to surface areas, or to continuously supply a producing well.

³⁴ Erlach *et al.* (2026), cited above.

³⁵ IFPEN (20 January 2025). Report cited above. New Caledonia offers real potential for hydrogen production in the ophiolites located in the Southern Massif around Prony Bay. However, this massif is highly fractured and lacks a natural geological cap capable of trapping the gas at depth. The discovery of reservoirs suitable for production via drilling appears uncertain.

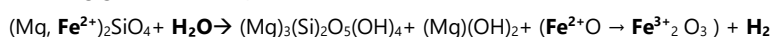
³⁶ During his interview on 28 May 2026, Laurent Truche pointed out that rock salt has a hydrogen permeability several orders of magnitude lower than that of clays, making it the only geological cap layer whose effectiveness in confining hydrogen has been demonstrated by the performance of underground geological hydrogen storage facilities.

³⁷ When clay is saturated with water, the water fills the pores and forces the hydrogen to dissolve slowly before diffusing.

³⁸ The water-to-rock ratio represents the volume of water available per unit volume of rock. In the context of serpentinisation, if this ratio is low, there is insufficient water to react with all of the olivine. Conversely, excess water can dissolve reaction products such as serpentine or magnetite and promote secondary reactions (such as carbonation).

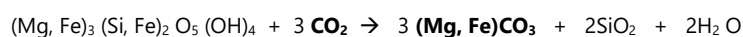
³⁹ Fresh water (low salinity) limits the solubility of minerals, promotes the precipitation of serpentine and accelerates the reaction kinetics. Hydrogen production will be maximised.

⁴⁰ The reaction of olivine with water leads to the formation of serpentine, as well as brucite, magnetite and hydrogen, according to the following geochemical equation:



Olivine Serpentine Brucite Magnetite

⁴¹ The precipitation of secondary minerals occurs during serpentinisation: secondary minerals are formed from the products of the main reaction. For example, serpentine produced from olivine reacts with carbon dioxide to form magnesite and siderite.



Serpentine

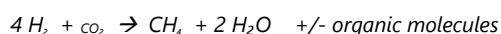
Magnesite/siderite

⁴² Thus, the precipitation of secondary minerals can also have a beneficial effect on serpentinisation. The transformation of primary minerals into secondary minerals is accompanied by an increase in the rock's volume of up to 30–40 per cent. If the distribution of secondary minerals generates asymmetrical mechanical stresses, the resulting volume expansion causes the rock to fracture at a microscopic scale. These new fractures allow water to penetrate deeper, providing access to new iron reserves and maintaining a high and continuous hydrogen yield over time.

⁴³ For example, serpentinisation peaks at 270°C, compared with 185°C for carbonation.

⁴⁴ Several indicators suggest a coupling between tectonics, fracturing and fluid flow that helps maintain the permeability of rocks that are potential sources of hydrogen, as well as reactive fracturing processes at the mineral scale.

⁴⁵ In the presence of catalysts (nickel, iron or cobalt), hydrogen can react with carbon dioxide to form methane.



The formation of methane (CH₄) through an abiotic reaction between hydrogen and carbon dioxide is accompanied by the permanent consumption of hydrogen, as methane is a stable end product.

⁴⁶ The reduction of sulphate (SO₄²⁻) by dihydrogen (H₂) produces hydrogen sulphide (H₂S) and water (H₂O).

⁴⁷ The maximum temperature at which microbial life is possible is estimated at 122°C. From 90°C onwards, the risk of microbial consumption of hydrogen is very low.

⁴⁸ There are three main types of hydrogen-consuming metabolic process:

- methanogenesis: bacteria (archaea) use hydrogen and CO₂ to produce methane;
- homoacetogenesis: bacteria reduce CO₂ using dihydrogen as an electron source to form acetate;
- sulphate reduction: bacteria use sulphate as the final electron acceptor instead of oxygen. In this process, hydrogen acts as the main electron donor, leading to the production of hydrogen sulphide.

⁴⁹ Lefeuvre *et al.* "Natural hydrogen migration along thrust faults in foothill basins: The North Pyrenean Frontal Thrust case study." *Applied Geochemistry*, 2022, 145, 105396.

⁵⁰ Hydroma, the company operating the Bourakébougou deposit, has reported production costs of \$0.50 per kilogram of hydrogen.

⁵¹ Lin *et al.* "Natural hydrogen techno-economics and valuation." *Applied Energy*, 2026.

⁵² Musa *et al.* "Techno-economic assessment of natural hydrogen produced from subsurface geological accumulations." *International Journal of Hydrogen Energy*, 2024, 93.

⁵³ Green hydrogen is produced by electrolysis of water using electricity from renewable sources, typically wind and solar power.

⁵⁴ Grey hydrogen is produced by steam reforming of natural gas or methane without capturing the co-generated greenhouse gases.

⁵⁵ Black hydrogen is generated by the gasification of coal.

⁵⁶ The two parameters with the greatest impact on the economic viability of natural hydrogen production are hydrogen concentration and production rate (see *above*).

⁵⁷ In Lorraine, a borehole drilled at Forchviller to a depth of 1,250 metres as part of the REGALOR research programme on methane trapped in coal seams has revealed gases dissolved in the aquifer of the Carboniferous formations in the following concentrations: 74 per cent methane, 18 per cent hydrogen and 8 per cent nitrogen. A new borehole drilled to a depth of 3,662 metres at the end of March 2026 confirmed the presence of hydrogen at a higher concentration, supporting the general observation that hydrogen content generally increases with depth. No official hydrogen concentration figures have yet been published. Given the relatively low concentration of gas in the groundwater, pumping the water to the surface to recover the gas is not feasible, either technically or economically. La Française de l'Énergie wishes to use Solexperts' SysMoG probe and its membrane technology to separate the gas from the water at depth. The pressure differential (over 100 bar) would enable the gas to be brought to the surface. However, these are breakthrough technologies currently under development, and their technical and economic feasibility has not yet been demonstrated.

⁵⁸ Musa *et al.* (2024), article cited above.

⁵⁹ Particularly in the presence of carbon dioxide and methane.

⁶⁰ A helium concentration of 0.3 per cent is sufficient to make its extraction commercially viable.

⁶¹ Interview with Emmanuel Masini, Chairman of Mantle 8, on 28 May 2026. A similar order of magnitude is put forward in the study by Erlach *et al.*, 2026, cited above: 'The Bourakébougou field in Mali is the only one where flow data from a well has been measured so far, amounting to 50 tonnes per year. Experts expect that flow rates several orders of magnitude higher are required for economic viability'.

⁶² Erlach *et al.* (April 2026). Study cited above. "Many of our interview partners expect large hydrogen deposits to be more likely and possibly limited to depths of several kilometres, where the hydrogen is not diminished by microbes. Since well pressure increases with depth, the given volume of a reservoir contains less hydrogen at shallower depths."

⁶³ The Oxford Institute for Energy Studies. *Natural (geologic) hydrogen and its potential role in a net-zero carbon future: Is all that glitters gold?* September 2024. As the smallest molecule, hydrogen is prone to leakage, highly reactive, and disperses easily into the air. Furthermore, although it has a very high gravimetric energy density (120 MJ/kg), significantly higher than that of most conventional fuels, including natural gas (55 MJ/kg), its volumetric energy density (9 MJ/l) is extremely low compared with that of conventional fuels (petrol has a volumetric energy density of 28 MJ/l). These characteristics make hydrogen particularly difficult to handle, as it generally needs to be either compressed or liquefied.

The liquefaction of hydrogen requires cryogenic temperatures of -253°C (compared with -160°C for LNG) and the process itself consumes more than 30 per cent of the hydrogen's energy content.

As regards the transport of hydrogen over long distances via fixed infrastructure, just as with natural gas, pipelines are generally considered the most cost-effective option as, in principle, they allow larger volumes of gas to be transported over long distances at a lower cost. This does not, however, mean that transporting hydrogen via pipeline will be as straightforward as transporting natural gas. Indeed, due to the physical properties of hydrogen, its transport is likely to be more expensive than that of natural gas, as more energy will be required to compress the fuel being transported and new types of compressors (centrifugal rather than reciprocating) will need to be installed more frequently. Furthermore, the pipelines themselves will require higher-quality (and therefore more expensive) steel to mitigate the risks of hydrogen embrittlement and leaks, whilst the use of repurposed natural gas infrastructure will most likely be limited due to the potential location of native hydrogen deposits, which are often far from industrial centres and existing pipelines.

This is why potential hydrogen deposits located near industrial hubs or regional centres represent the preferred business model for exploration companies: a regional market model could facilitate a reliable and cost-effective supply of hydrogen for local industries. Thus, the potential extraction of natural hydrogen at the Forschviller site in Moselle is intended to supply the steel industries of the Saarland.

⁶⁴ Exploration and service companies are therefore forced to purchase seismic data reprocessed by the BRGM or directly from operators. In Australia, all subsurface data is in the public domain and is managed by the state.