The place of natural hydrogen in the energy transition: A position paper

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*Natural Hydrogen is a new, clean and low-carbon source of hydrogen that is produced by the Earth, and can migrate and accumulate in geological reservoirs. Its exploration has begun in many countries and its price could be significantly lower than other H_2 sources. In this position paper, the **earth₂ initiative** summarizes (i) what natural hydrogen is, (ii) how we explore and produce it, (iii) the benefits of this new resource, (iv) the maturity of the technology, (v) the presence of a very active community, (vi) the potential growth for this business, (vii) the need for regulatory evolution and appropriate taxonomy at European level and (viii) the next steps in natural H_2 development, considering the needs for investments in demonstration systems and pilots.*

*L'hydrogène naturel est une nouvelle source d'hydrogène propre et à faible teneur en carbone qui est produite par la Terre et qui peut migrer et s'accumuler dans des réservoirs géologiques. Son exploration a commencé dans de nombreux pays et son prix pourrait être nettement inférieur à celui des autres sources de H_2. Dans cette prise de position, l'**initiative earth₂** résume (i) ce qu'est l'hydrogène naturel, (ii) comment nous l'explorons et le produisons, (iii) les bénéfices de cette nouvelle ressource, (iv) la maturité de la technologie, (v) la présence d'une communauté très active (vi) le potentiel de croissance de cette activité, (vii) la nécessité d'une évolution réglementaire et d'une taxonomie appropriée au niveau européen et (viii) les prochaines étapes du développement naturel de H_2, compte tenu des besoins d'investissements dans des systèmes de démonstration et de projets pilotes.*

*El Hidrogeno Natural es una fuente nueva, limpia y de bajo carbono, que es producida por la Tierra, que puede migrar y acumularse en reservorios geológicos. Su exploración ha comenzado en muchos países y su precio puede ser significativamente más bajo que otras fuentes de H_2. En este trabajo, la **iniciativa earth₂** resume (i) que es el hidrogeno natural, (ii) como se explora y produce, (iii) los beneficios de este recurso, (iv) la madurez de esta tecnología, (v) la presencia de una comunidad muy activa, (vi) el potencial crecimiento de este negocio, (vii) la necesidad de una evolución regulatoria y la taxonomía adecuada a nivel europeo y, (viii) los siguientes pasos en el desarrollo natural del H_2, considerando las necesidades de inversión en sistemas pilotos y de demostración.*

1. What is Natural Hydrogen? Where can we find it?

The Earth continuously produces natural H_2 (also called Native H_2) through several chemical reactions that are primarily related to the oxidation of ferrous iron minerals, radiolysis of water, maturation of organic matter and the outgassing from the Earth's mantle:

- Redox reactions related to the presence of ferrous iron in certain minerals or to ferrous iron dissolved in aquifers are the most efficient processes for producing H_2. In these reactions, the ferrous iron rusts and scavenges oxygen from the water, releasing hydrogen (eq. 1):

$$2\ FeO + H_2O = Fe_2O_3 + H_{2(aq)} \quad \text{(eq.1)}$$

These reactions can be made with (a) dissolved ferrous iron, (b) olivine and pyroxene minerals of the Earth's Mantle (serpentinisation), (c) ferrous iron-rich minerals of the Earth's crust (Biotite, Amphiboles, Pyrite, Pyrrhotite, Magnetite, etc…), and to a lesser extent, with ferrous iron-rich carbonates (Siderite, Ankerite) [1].

- The radiolysis of water produces H_2 by splitting the water molecule through radiation emitted by the decay of natural radioactive atoms (U, Th, etc…) present in several types of rocks [2, 3].
- The Earth stored hydrogen during its primordial accretion, in the form of hydrides that could gradually decompose and support continuous H_2 outgassing over geologic time [4].
- Over-maturation of organic matter can generate natural H_2 [5].
- The decomposition of volcanic H_2S gas into H_2 and SO_2 explains the concentrations obtained in the fumaroles of volcanos [1].

The exploration strategy for hydrogen should focus on areas where ferrous iron and/or natural radioactivity is present and can react with water [6, 7]. Magmatic rocks are therefore of primary importance, and many occurrences of H_2 seepages are known on continental or offshore regions related to these rocks. In an exhaustive

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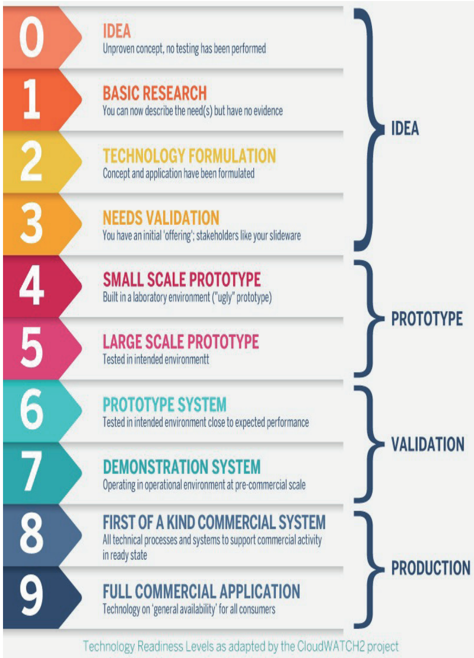

TRL Native H_2 Exploration/Production

0 Discovery of H_2 at the Earth surface	Done
1 Systematic research of H_2 seepages in various environments	Done
2 Short time monitoring of sites	Done for 2-3 sites
3 Understanding of the origin of H_2	Done for 2-3 sites
4 Small Scale prototype of permanent H_2 fluxes / Numerical modelling of the H_2 permanent seepages Global understanding of the Hydrogen system	In Progress in Academia
5 Median Scale prototype (1200 m) Perennial production of a demonstrator over several years	Hydroma (Mali)
6 First deep borehole (3000 – 5000 m)	Natural hydrogen energy LLC Desert Mountain Energy
7 First Exploration plan at regional scale First delineation / Several boreholes	In progress Santos (Australia)
8 Prototype of Production of the first discovery	No
9 Scaling-up / Commercial exploitation	No

Figure 1: Evaluation of the technology maturity using the Technology Readiness Levels (TRL) method.

review, Zgonnik (2020) [8] recorded H_2 occurrences in 465 geo-references worldwide. Extensive reviews of available data are also being conducted on a national level, for example in Australia [9].

Two emblematic sites can illustrate the potential of natural H_2:

- The Bourakebougou site (Mali) has 12 positive boreholes with pure H_2 (98%) over a surface of 50 km² [10].
- In Iceland, geothermal power plants emit a total of 1.2 kt H_2 per year into the atmosphere. If we consider a price of H_2 for 2€/kg, the natural H_2 emitted by the existing power plants corresponds to a value of €2.3 M/yr [11].

Natural H_2 is a viable resource that is observed as being relatively well distributed across the Earth's surface. Economic reserve assessments are underway in some locations.

N.B.: In this paper, we use the expression "Natural hydrogen" but this is equivalent to Native Hydrogen, GeoH_2 or White Hydrogen. We also find "Gold Hydrogen" in some publications for the same natural origin.

2. How do we Explore and Produce Natural H₂?

The geological exploration of H_2 follows the same approach as for hydrocarbons, starting with the identification of the source rock, followed by the migration pathways, and finally the reservoirs and traps. For the latter, formations such as volcanic sills, clays or salt layers could potentially be capable of trapping hydrogen in crystalline or sedimentary rocks, for example, at the bottom of the sedimentary basins.

In the case of Bourakébougou, boreholes of less than 1000 m seem to be effective in finding significant quantities of natural hydrogen. However, H_2 is a very reactive molecule, that can be consumed by many oxidants, and therefore, it is destroyed during its migration. Bacterial growth can also be promoted by natural hydrogen, as it acts as an energy provider for the microbes. Therefore, a temperature above 120°C can preserve the resource by eliminating microbial activity while increasing the kinetics of the reactions. Future exploration and production schemes should integrate the chemical and biological reactivity of this molecule. However, if the H_2 flux is high, the reactivity of the molecules will be less crucial.

Some players are also contemplating the co-production of He with natural H_2, as they are commonly found together. Geothermal power plants could enhance their value chains by co-producing natural H_2 and mineral substances, such as lithium. Coupling H_2 production with the storage of CO_2 in ultrabasic rocks will add additional benefits to natural H_2 production [12].

3. The benefits of Natural Hydrogen

The earth$_2$ members are convinced that the energy transition requires all sources of clean hydrogen to succeed. Natural hydrogen offers specific advantages:

1. Natural hydrogen is clean, as there is no carbon in the production chain, and does not require anthropogenic electricity or water. Furthermore, extraction and separation at production sites have a limited footprint.
2. It is not an energy vector, but a resource in itself, and does not require the destruction of one energy source for another. It does not depend on anthropogenic energy or specific raw materials.
3. Recent research targeting various countries worldwide suggests the presence of multiple viable plays and cost-effective exploitable resources.
4. The production sites available within the European continent, such as France, Spain, Italy, Poland and Romania, offer diversity and flexibility. It can complement other low carbon H_2 production means and it can contribute to securing energy supply and avoiding the supply's intermittency.
5. Natural H_2 does not require purified water (electrolysis-based Green H_2

production), or CO_2 storage (Blue H_2). Additionally, it does not involve waste disposal (nuclear-driven Pink H_2).

6. No production intermittency.
7. The production costs of natural H_2 are expected to be lower than all other forms of proposed H_2 production, which can help in unlocking the hydrogen economy [12]. The very competitive production cost is reinforced by a joint valorisation potential of resources, such as helium, geothermal energy and high-value brines.

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4. Maturity of the Technology

Our ultimate goal is to produce a commercial H_2 resource at a limited cost and with minimal environmental impacts. To achieve this, we can use the Technology Readiness Levels scale (TRL) to assess its maturity (Figure 1).

We assign a TRL of 9 to the ultimate achievement of commercial production of natural H_2.

The TRL 0 corresponds to the discovery of H_2 seepages at the Earth's surface, with the idea that larger volumes can be produced underground [14].

The TRL 1 corresponds to the systematic search of H_2 seepages in various geological environments [8].

The TRL 2 corresponds to the first short-term monitoring of H_2 fluxes [7, 15].

The TRL 3 corresponds to a global understanding of the origin of H_2 emissions in continental settings, as demonstrated by the model of production proposed by Lefeuvre et al. [16] for the West Pyrenees, or the potential for economic production of natural H_2 in the geothermal fields of Iceland [11].

The TRL 4 corresponds to the implementation of permanent monitoring sites that couple hydrogeology, hydrochemistry and gas chemistry in very well-characterised geological structures coupled with well tests to determine the reserve volume.

The TRLs 5 and 6 correspond to investments that will enable to access depths where active H_2 production processes are taking place. A TRL 5 or 6 can be assigned to the Bourakébougou site in Mali [10, 17], where perennial H_2 production has been demonstrated with 12 wells showing its presence. However, the local company HYDROMA has not reported a reserve estimate at the production site.

After delineation at a regional scale (TRL7), commercial production tests can be carried out (TRL 8), and finally, the H_2 gas can be commercialised (TRL9). Several exploration companies are making rapid progress towards this ultimate goal.

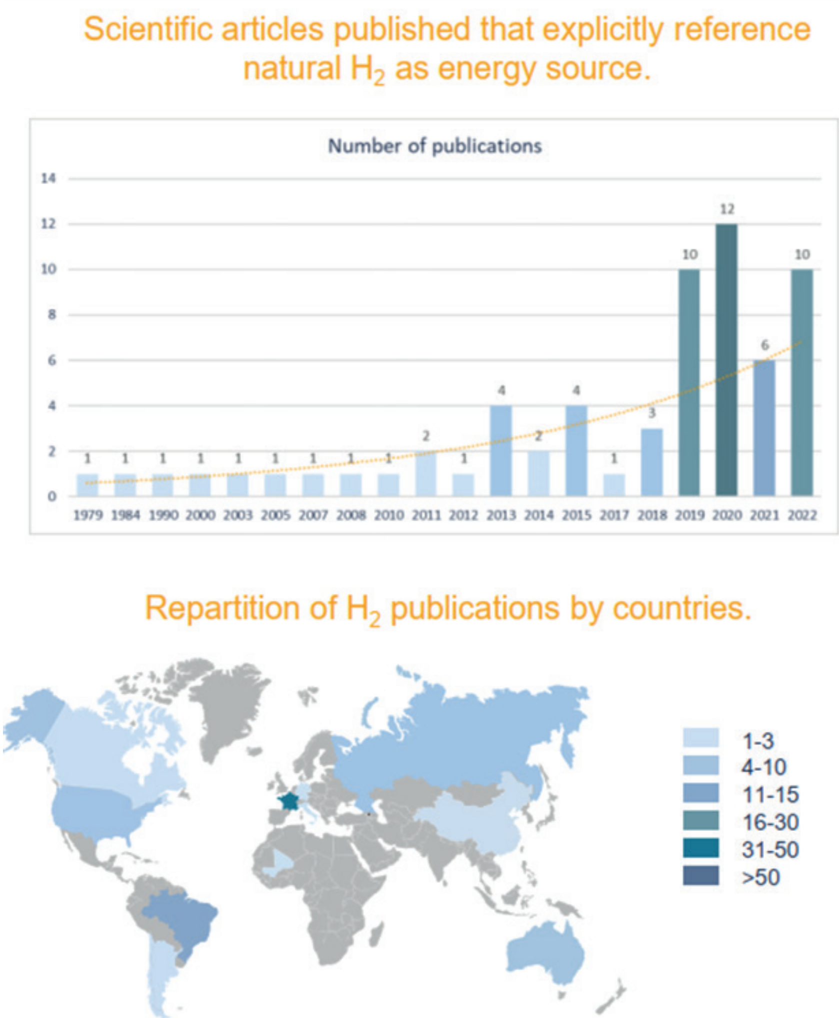

Figure 2: (a) Progress of the number of publications related to natural H_2 and (b) repartition of natural H_2 publications by country.

5. A Very Active Scientific Community

A scientific community dedicated to natural H_2 already exists in France, the United Kingdom, the USA, Brazil, Australia and other countries. This community consists of research groups that have worked on water-rock interaction processes (such as serpentinisation and radiolysis) or economic geology (such as in oil and gas or mining industries). The number of publications presenting data showing explicit natural H_2 presence in soils, aquifers or wells is rapidly increasing (Figure 2).

A dedicated congress now exists on this subject (H-Nat), which was held online in 2021 and 2022. Special sessions have been organised at the AAPG Europe Regional Conference in Budapest (May 2022), at the Goldschmidt Conference in Hawaii (2022) and in Lyon (2023).

6. Potential Growth of a Natural Hydrogen Business

The economic sector is in the process of being structured for natural H_2 and the earth$_2$ initiative is a good example of this in Europe. The earth$_2$ initiative brings together energy groups like Engie, exploration and production start-ups such as 45-8 Energy, H_2Au, Helios Aragon, service providers including the CVA group and Schlumberger, and independent consultants. The earth$_2$ initiative is composed of 40 members actively working in this field. This initiative was born under the aegis of the Avenia cluster and these actors develop exploration methods, geochemical sensors and geophysical methods dedicated to natural H_2 exploration. earth$_2$ is a forum for fruitful discussions on the commercial development of natural H_2 through permanent working groups, workshops and field trips, launching innovative, and collaborative projects and lobbying public institutions.

In Australia, several start-ups and oil and gas companies now have an exploration strategy for natural H_2, including Petrex, Buru Energy and Gold Hydrogen. In South Australia, more than 20 permits have been applied for, with two already granted to Gold H2 and one to H2EX. The first wells are expected in 2023. Further north, in the Amadeus Basin, Santos, an oil company, has "accidentally" encountered a mixture of methane, helium and hydrogen and will drill three wells in 2023 to evaluate the resource.

In the USA, two companies have reported significant discoveries: Natural Hydrogen Energy LLC in Nebraska in 2019 and Desert Mountain Energy in Arizona in 2022.

By the end of 2022, 27 companies have been identified as active in natural hydrogen exploration, up from three companies three years ago.

The American Association of Petroleum Geologists has also established a "Natural Hydrogen" task force led by the US Geological Survey. Meanwhile, the International Energy Agency has accepted a technical task on natural H_2 in its H_2 collaboration program.

The costs of natural hydrogen production are expected to be significantly lower than the production costs of steam-methane reforming (brown H_2: 1.5$/kg). Indeed, the exploration and production costs of natural hydrogen are anticipated to be very similar to those of natural gas, without the need for refinery transformation or CO_2 storage (blue hydrogen: 3$/kg = brown H_2 + costs of CO_2 storage). Currently, green H_2 from renewables costs over $6/kg and requires electricity transformation that could be used directly for other purposes. Our best estimate for the price of natural H_2 is less than $1/kg.

7. Regulatory Aspects of H_2 Exploration

The development of H_2 exploration requires changes in legislation to allow companies to obtain permits and perform exploration works. Mali is a pioneer country, where the first permit was granted in the area of Bourakébougou in 2017. South Australia opened its mining code to natural hydrogen exploration in 2021. In April 2022, it was France's turn to include natural H_2 as a natural resource in its mining code and the US law on natural substances also appears to be flexible enough to allow for H_2 exploration permits.

8. Recommended Next Steps of Natural H_2 Development

Natural Hydrogen is a topic that is rapidly shifting from pure research to economic development. This new energy source is clean with very low-carbon emissions and should be considered as a form of renewable hydrogen in European taxonomy. Its potential is already demonstrated and significant volumes have been identified in regions such as Iceland, Mali and the Pyrenees, where exploration licenses have been granted. However, public support is still needed to develop demonstration systems and pilots in promising areas. Access to financing means, available for the hydrogen economy, could accelerate the maturity and the number of projects. Ultimately, regulation changes are required to facilitate the development of this subject.

The members of the earth$_2$ initiative are optimistic about the potential for this new resource and believe that it will require support to demonstrate and contribute to the energy transition.

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References

[1] Klein, F., Tarnas, J.D. and Bach, W. (2020) Abiotic sources of molecular hydrogen on Earth. Elements 16, 19-24.

[2] Sherwood-Lollar B, Onstott TC, Lacrampe-Couloume G, Ballentine CJ (2014) The contribution of the Precambrian continental lithosphere to global H_2 production. Nature 516: 379382

[3] Truche, L., Joubert, G., Dargent, M., Martz, P., Cathelineau, M., Rigaudier, T. and Quirt, D. (2018) Clay minerals trap hydrogen in the Earth's crust: Evidence from the Cigar Lake uranium deposit, Athabasca. Earth and Planetary Science Letters 493, 186-197.

[4] Toulhoat, H. and Zgonnik, V. (2022) Chemical Differentiation of Planets: A Core Issue. Astrophysical Journal 924.

[5] Horsfield, B., Mahlstedt, N., Weniger, P., Misch, D., Vranjes-Wessely, S., Han, S. and Wang, C. (2022) Molecular hydrogen from organic sources in the deep Songliao Basin, P.R. China. International Journal of Hydrogen Energy 47, 16750-16774.

[6] Gaucher, E.C. (2020) New perspectives in the industrial exploration for native hydrogen. Elements 16, 8-9.

[7] Moretti, I., Brouilly E., Loiseau K., Prinzhofer A., Deville E. (2021). Hydrogen emanations in intracratonic areas: new guidelines for early exploration basin screening. Geosciences 2021, 11, 145.

[8] Zgonnik, V. (2020) The occurrence and geoscience of natural hydrogen: A comprehensive review. Earth-Science Reviews 203.

[9] Boreham, C.J., Edwards, D.S., Czado, K., Rollet, N., Wang, L., van der Wielen, S., Champion, D., Blewett, R., Feitz, A. and Henson, P.A. (2021) Hydrogen in Australian natural gas: occurrences, sources and resources. The APPEA Journal 61, 163-191.

[10] Prinzhofer, A., Tahara Cissé, C.S. and Diallo, A.B. (2018) Discovery of a large accumulation of natural hydrogen in Bourakebougou (Mali). International Journal of Hydrogen Energy 43, 19315-19326.

[11] Combaudon, V., Moretti, I., Kleine, B.I. and Stefánsson, A. (2022) Hydrogen emissions from hydrothermal fields in Iceland and comparison with the Mid-Atlantic Ridge. International Journal of Hydrogen Energy 47, 10217-10227.

[12] Osselin, F., Soulaine, C., Fauguerolles, C., Gaucher, E.C., Scaillet, B. and Pichavant, M. (2022) Orange hydrogen is the new green. Nature Geoscience, 15, 765–769.

[13] Lapi, T., Chatzimpiros, P., Raineau, L. and Prinzhofer, A. (2022) System approach to natural versus manufactured hydrogen: An interdisciplinary perspective on a new primary energy source. International Journal of Hydrogen Energy 47, 21701-21712.

[14] Smith NJP (2002) It's time for explorationists to take hydrogen more seriously. First Break 20: 246-253.

[15] Lefeuvre, N., Truche, L., Donzé, F.-V., Ducoux, M., Barré, G., Fakoury, R.-A., Calassou, S. and Gaucher, E.C. (2021) Native H_2 Exploration in the Western Pyrenean Foothills. Geochemistry, Geophysics, Geosystems 22, e2021GC009917.

[16] Lefeuvre, N., Truche, L., Donzé, F.V., Gal, F., Tremosa, J., Fakoury, R.A., Calassou, S. and Gaucher, E.C. (2022) Natural hydrogen migration along thrust faults in foothill basins: The North Pyrenean Frontal Thrust case study. Appl. Geochem., 105396.

[17] Rigollet, C. and Prinzhofer, A. (2022) Natural Hydrogen: A New Source of Carbon-Free and Renewable Energy That Can Compete With Hydrocarbons. First Break 40, 78-84.