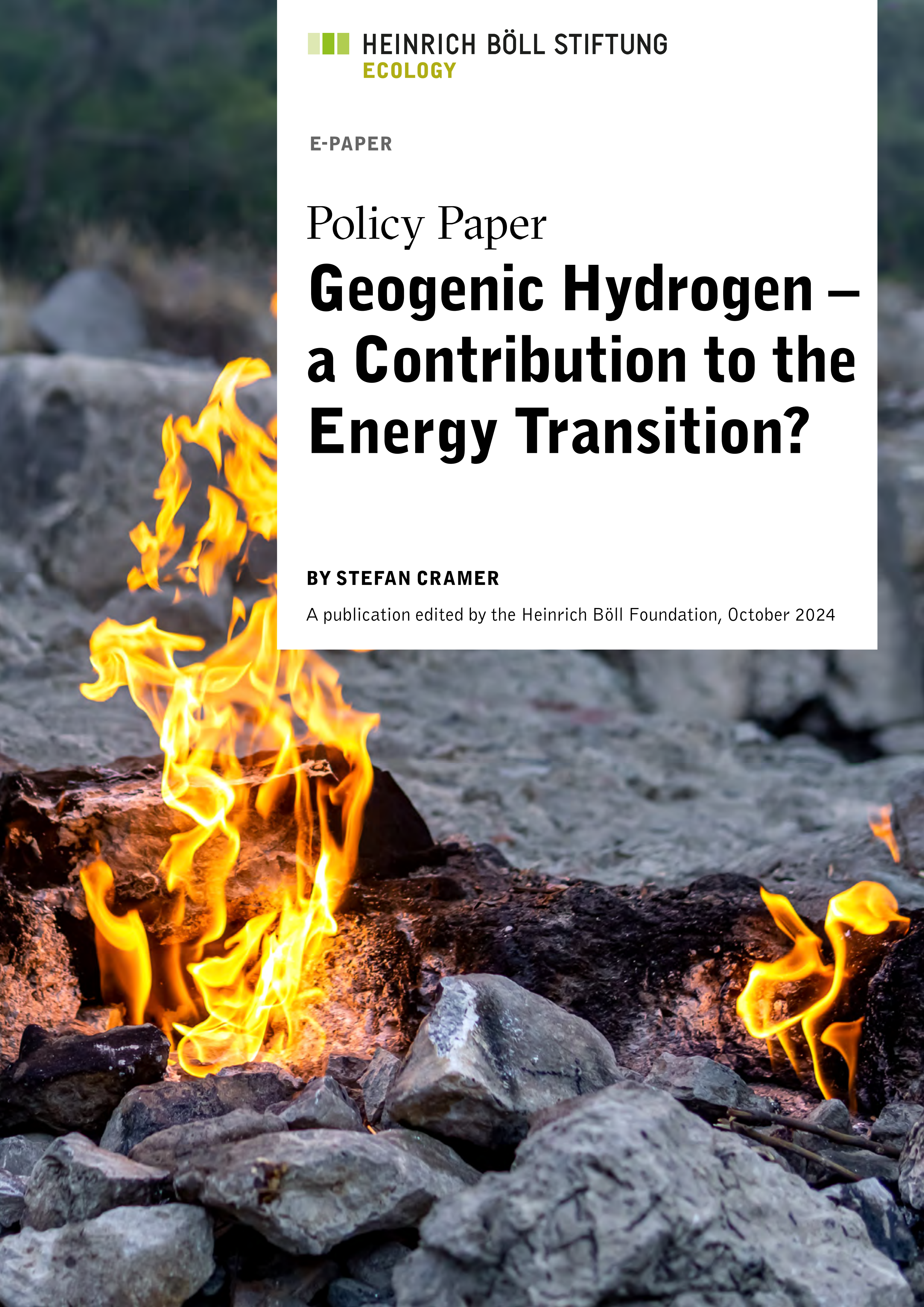

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Policy Paper

Geogenic Hydrogen – a Contribution to the Energy Transition?

BY STEFAN CRAMER

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By Stefan Cramer

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Foreword

To stop the main driver of the climate crisis, the rapid phase-out of fossil fuels remains top priority. For certain applications such as steel production and long distance transport by sea and air, hydrogen and its derivatives will likely play a key role. Up to now, the focus for the energy transition of these sectors has been on green hydrogen that is produced by electrolysis on the basis of electricity generated from renewable sources. However, it remains an expensive and scarce solution.

Recent reports have raised the interest in geogenic or «white» hydrogen that can be found in certain geological formations. We wanted to know more about geogenic hydrogen, its potential and risks and asked Dr. Stefan Cramer to review the literature and provide an overview of the current state of knowledge on geogenic hydrogen and its potential role.

A lot is still unknown in this respect. We hope that this paper is useful as a first introduction into the current state of knowledge.

Berlin, November 2024

Jörg Haas, *Head of the Globalisation and Transformation Division at the Heinrich-Böll-Foundation*

Geogenic Hydrogen – a Contribution to the Energy Transition?

«White» or «geogenic» hydrogen does not play a prominent role in the current debate about hydrogen and its role in the energy transition as a possible new «carbon-free» energy source. The general public is still in the dark regarding its existence, let alone its potential. But some energy experts consider it an interesting alternative to the energy-inefficient and expensive production of hydrogen from fossil or renewable resources. Exploration for geogenic hydrogen takes place virtually across the globe. Researchers are scrambling to identify the sources and delineate resources. But is there a real chance? Could it become an economically viable energy source? And will it arrive in time to have an impact on combating harmful climate change?

Box 1: What is geogenic hydrogen?

For the subject of this study, we use the term of «geogenic hydrogen». However, different authors and various publications also use many synonymous terms like white[1], golden[2], geologic, natural, native, subsurface[3] or abiogenic hydrogen and probably more for the same thing: geogenic hydrogen refers to hydrogen, that is generated through geological processes within the Earth.

Box 2: Hydrogen color code

Colour	Fuel	Process	Products
White/Golden		Extraction and purification of naturally occuring hydrogen	H_2 and associated gases (CO_2, CH_4, $H2_S$, N_2, He)
Black/Brown	Coal	Steam reforming or gasification	$H_2 + CO_2/CO$ (released)
Grey	Natural gas	Steam reforming	$H_2 + CO_2$ (released)
Blue	Natural gas	Steam reforming	$H_2 + CO_2$ (captured and stored)
Turquoise	Natural gas	Pyrolysis	H_2 + C (solid)
Red	Nuclear power	Thermolyis/Catalytic splitting	$H_2 + O_2$
Purple/Pink	Nuclear power	Thermolyis/Electrolysis	$H_2 + O_2$
Yellow	Solar power	Electrolysis	$H_2 + O_2$
Green	Renewable Electricity	Electrolysis	$H_2 + O_2$

1 Kocher, J., 2024: *Die Jagd nach natürlichem Wasserstoff hat begonnen* geo, 25.04.2024.
2 McFarland, E., 2024: *Golden hydrogen—or fool's gold?* -Bulletin of the Atomic Scientists, March 6, 2024.
3 Earth2 (n. d.): *https://www.earth2-hydrogen.com/en/home*.

White/Golden: White or golden hydrogen is geogenic hydrogen, that is generated through geological processes within the Earth. It is also known as geologic, natural, native, subsurface or abiogenic hydrogen.

Black/Brown: Black or brown hydrogen is produced through gasification or steam reforming of black or brown coal. The byproducts carbon dioxide and carbon monoxide are released to the atmosphere.

Grey: Grey hydrogen is produced from natural gas or methane by steam reforming or gasification. Greenhouse gases as byproducts such as carbon dioxide are released to the atmosphere.

Blue: Blue hydrogen is essentially produced in the same way as grey hydrogen, but combined with carbon capture and storage (CCS).

Turquoise: Turquoise hydrogen is produced by pyrolysis (thermal splitting) of natural gas /methane. Solid carbon is removed as a byproduct instead of gaseous carbon dioxide.

Purple/Pink: Purple hydrogen is produced through combined chemo-thermal electrolysis of water using nuclear power and heat. Pink hydrogen is created through electrolysis powered by nuclear energy.

Red: Red hydrogen is generated through high-temperature catalytic splitting of water by using nuclear heat.

Yellow and Green: Green hydrogen is generated through electrolysis of water by using electricity produced by renewable energy sources, such as wind or solar power. Hydrogen generated through electrolysis using solar power is sometimes called yellow hydrogen.

Sources:
H2bulletin (n. d.): Hydrogen colours codes, *https://h2bulletin.com/knowledge/hydrogen-colours-codes*.
Nationalgrid (n. d.): The hydrogen colour spectrum, *https://www.nationalgrid.com/stories/energy-explained/hydrogen-colour-spectrum*.
Ricardo (2021): Cracking Hydrogen colour codes, *https://www.ricardo.com/en/news-and-insights/insights/hydrogen-colour-codes-explained*.

A New Gold Rush for Hydrogen

Extracting naturally occurring hydrogen has the potential to be a cost-effective and environmentally friendly method of producing hydrogen, helping in the transition to a decarbonized energy system.

A good starting point is the interactive world map on hydrogen exploration of H2Today at *https://hydrogentoday.info/en/hydrogen-world/.*

According to recent research by Rystad Energy[4], the number of companies actively searching for natural hydrogen deposits has significantly increased, with 40 companies engaged in exploratory efforts at the end of 2023, up from just 10 in 2020. Currently, exploration activities are taking place in various countries including Australia, the US, Spain, France, Albania, Colombia, South Korea, and Canada.

Geogenic hydrogen has been **observed for thousands of years**. The most famous example are the eternal flames on Mount Chimaera in Turkey[5], which is said to have lit the flames for the Olympic fire more than 2500 years ago. In modern times, 100 years ago, a borehole in Australia yielded hydrogen and was closed off as a nuisance. The most recent history of geogenic hydrogen started with a bang, an explosion of a borehole for water in Mali[6],[7] in 1987, and several underground explosions in the Bulqizë chromite mine in Albania[8]. In both cases it was considered a dangerous nuisance, not an asset. It took the foresight of an ingenious (and controversial) Malian businessman and politician, Aliou Diallo, to explore this further. He is the founder and CEO of Hydroma Inc., which focuses on the research and use of geogenic hydrogen at Bourakébougou, a village near Bamako. This is still the only sizeable hydrogen field in the world continuously producing hydrogen from 30 wells. The

4 Dokso, A., 2024: Numbers of Companies Searching for Natural Hydrogen Increases - H2 energy news 18. 03. 2024.

5 Etiope, G., 2023: *Massive release of natural hydrogen from a geological seep (Chimaera, Turkey): Gas advection as a proxy of subsurface gas migration and pressurised accumulations* - International Journal of Hydrogen Energy, Volume 48, Issue 25, 2023, Pages 9172-9184, ISSN 0360-3199, *https://doi.org/10.1016/j.ijhydene.2022.12.025*.

6 Prinzhofer, Alain, Cheick Sidy Tahara Cissé, Aliou Boubacar Diallo, 2018: Discovery of a large accumulation of natural hydrogen in Bourakebougou (Mali) - International Journal of Hydrogen Energy, Volume 43, Issue 42, 2018, Pages 19315-19326, ISSN 0360-3199, *https://doi.org/10.1016/j.ijhydene.2018.08.193*.

7 Maiga, Omar, Deville, Eric, Jérome Laval, Prinzhofer, Alain, Diallo, Aliou Boubacar, 2024: Trapping processes of large volumes of natural hydrogen in the subsurface: The emblematic case of the Bourakebougou H2 field in Mali - International Journal of Hydrogen Energy, Volume 50, Part B, 2024, Pages 640-647, ISSN 0360-3199, *https://doi.org/10.1016/j.ijhydene.2023.10.131*.

8 Truche, L., et al., 2024: A deep reservoir for hydrogen drives intense degassing in the Bulqizë ophiolite *Science, 8 Feb 2024, Vol 383, Issue 6683*, pp. 618-621, DOI: 10.1126/science.adk9099.

industry is eagerly awaiting another success story of a hydrogen «play», that could start producing economically in the near term.

Since then, a series of new discoveries has led to a small «gold rush» of exploration on virtually all continents. A similar story played out in **Albania**. Geologists recently reported that more than 200 tons of hydrogen per year were flowing from the Bulqizë chromite mine in Albania[9] . Here, approx. 1 500 m^3 hydrogen per day are observed. We will refer to these two examples more often in this context as they stand for very different types of «natural hydrogen systems».

In September 2023, French researchers stumbled across a large underground hydrogen deposit in the **Lorraine** region.[10] This is reported to be the largest deposit until now in the world. It is estimated that there are approx. 46 million tons of hydrogen stored at up to 3 000 meters below surface. This would be equivalent to half of the current global hydrogen production of around 90 million tons of hydrogen per year. France has already amended its mining code to allow for extraction of geogenic hydrogen.

Similar promising discoveries have been made in the **French**[11] **and Spanish Pyrenees**[12] and in the **French and Italian Alps**[13]. In Italy's **Lardarello** region[14] hydrogen sources have been identified. More sites have been identified in Poland and Romania.

9 Truche, L., et al., 2024: A deep reservoir for hydrogen drives intense degassing in the Bulqizë ophiolite, *Science, 8 Feb 2024, Vol 383, Issue 6683*, pp. 618-621, DOI: 10.1126/science.adk9099.

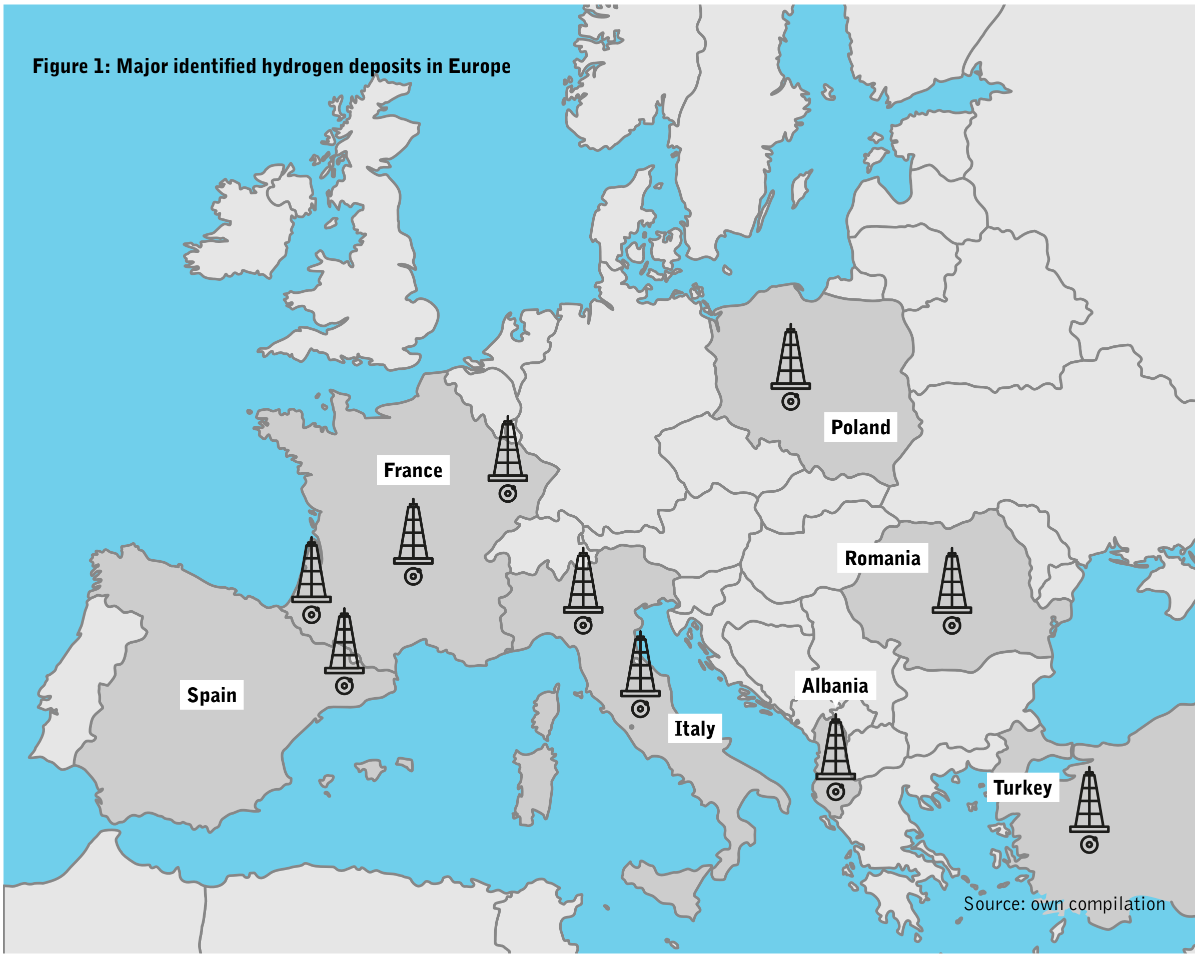
10 von Brackel, B., 2024: *Natürlicher Wasserstoff: Neue Ära in der Energiegewinnung?* – Süddeutsche Zeitung, 15.1.2024.

11 Dokso, A., 2023: Spain to extract Europe's first subterranean hydrogen deposit – H2 energy news, 29.03.2023, *https://energynews.biz/spain-to-extract-europes-first-subterranean-hydrogen-deposit/#-google_vignette*.

12 Lefeuvre, N., Truche, L., Donzé, F.-V., Gal, F., Tremosa, J., Fakoury, R.-A., Calassou, S., Gaucher, E.C., 2022: Natural hydrogen migration along thrust faults in foothill basins: The North Pyrenean Frontal Thrust case study, Applied Geochemistry, Volume 145, 2022, 105396, ISSN 0883-2927, *https://doi.org/10.1016/j.apgeochem.2022.105396*.

13 Dugamin, E., Truche, L. Donzé, F.V. (n. d.): Natural Hydrogen Exploration Guide - Laboratoire ISTerre, Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, IRD,IFSTTAR, 38000 Grenoble, France.

14 Leila, M., Levy, D, Piccardi, L., Moretti , I., 2021: *Origin of natural hydrogen discharging from geothermal fumarolic emissions in Monterotondo, Tuscany region, Italy* – Societé Géologique de France, L'hydrogène naturel : état de la recherche en France.

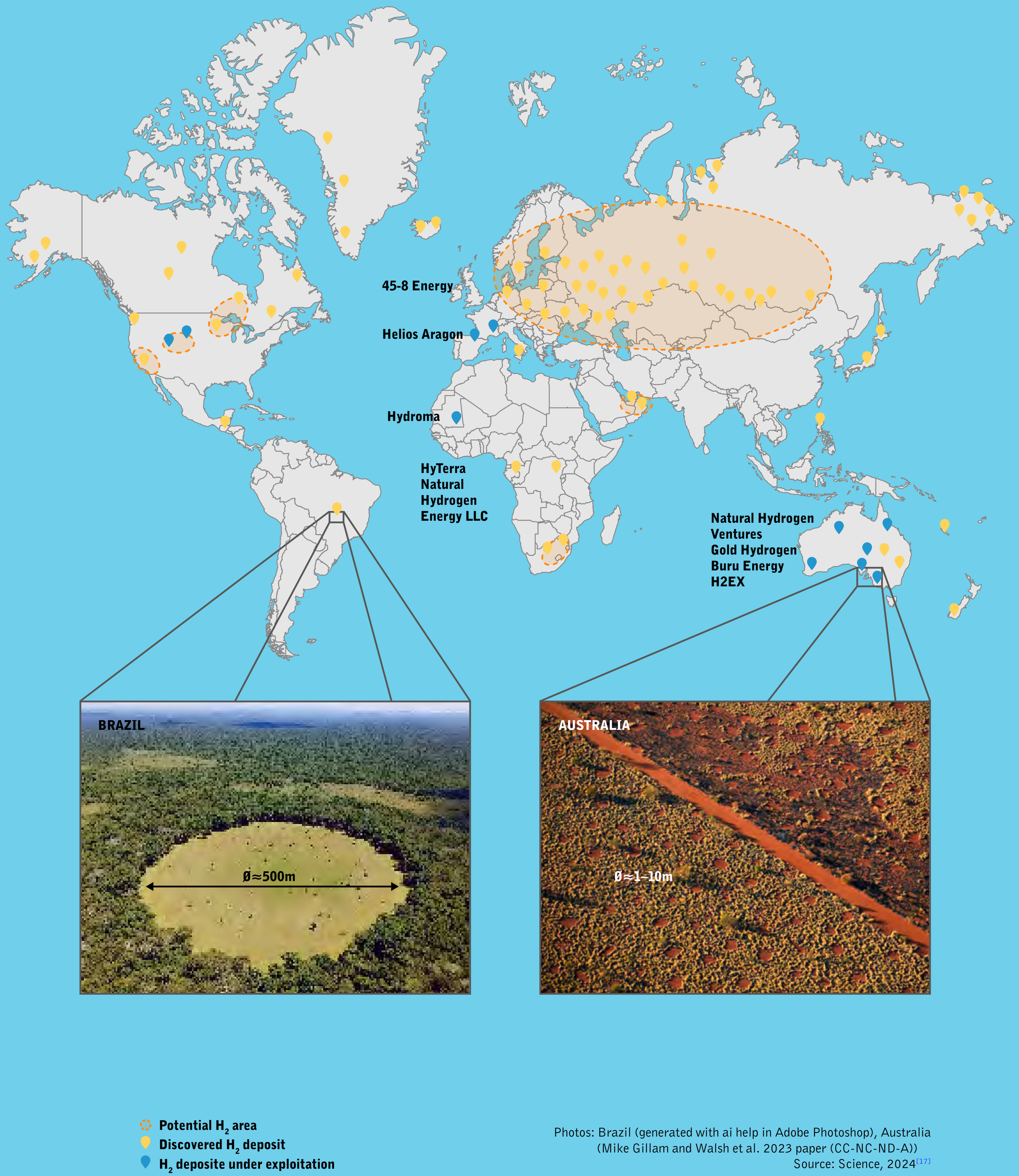


The first comprehensive **list of hydrogen deposits**[15] was compiled in 2019 by the Ukrainian researcher Viacheslav Zgonnik, CEO of the company «Natural Hydrogen Energy», claiming to have now drilled the **first successful borehole** in **Kansas**[16].

15 Zgonnik, V., 2019: *The occurrence and geoscience of natural hydrogen: A comprehensive review* – *https://doi.org/10.1016/j.earscirev.2020.103140*.

16 Natural Hydrogen Energy LLC, 2020: Promotional Video: *«Did you know that hydrogen can be natural?»*, *https://www.youtube.com/watch?v=Nu6ye8oY310&t=3s&themeRefresh=1* (only online).

Figure 2: Status of known geogenic hydrogen projects (in Jan. 2024)



Photos: Brazil (generated with ai help in Adobe Photoshop), Australia (Mike Gillam and Walsh et al. 2023 paper (CC-NC-ND-A))
Source: Science, 2024[17]

Geoffrey Ellis of the US Geological Survey (USGS) **formulated the main research questions**[18] on geogenic hydrogen and convinced the USGS to launch a comprehensive research programme. He also compiled the first, and still unchallenged, calculations of the **quantities, that might be out there**.[19] Recently, Chinese authors summarized their combined knowledge on natural hydrogen.[20] They have studied the potential for natural hydrogen, that is absorbed in commercial quantities **in clay formations**.[21]

The so-called fairy circles in Namibia[22] (see Fig. 3) offered a first glimpse into a global prospection strategy, as they can be easily identified in aerial photography. However, the reliability of fairy circles has not been proven, there is nothing today that makes it possible to predict or localize a deposit in advance and to estimate global hydrogen deposits. Some economists in Namibia fear that the country's massive investment into green hydrogen[23] may be jeopardized if exploration for geogenic hydrogen is ever successful.

17 Blay-Roger, R., Bach, W., Bobadilla, L.F., Ramirez Reina, T, Odriozola, Amils, R., Blay, V., 2023: Natural hydrogen in the energy transition: Fundamentals, promise, and enigmas - Renewable and Sustainable Energy Reviews, Elsevier, 21.10.2023 (online) *https://doi.org/10.1016/j.rser.2023.113888.*

18 Ellis, G., 2023: USGS: The Potential of Geologic Hydrogen for Next-Generation Energy - A previously overlooked, potential geologic source of energy could increase the renewability and lower the carbon footprint of our nation's energy portfolio: natural hydrogen – Website Central Energy Resources Science Center, United States Geological Survey (USGS): *https://www.usgs.gov/news/featured-story/potential-geologic-hydrogen-next-generation-energy*.

19 Ellis, G, Gelman, D., 2022: A Preliminary Model of Global Subsurface Natural Hydrogen Resource Potential – *Presentation* at GSA Connects 2022 meeting in Denver, Colorado, Session No. 215, Development Status of Non-Petroleum Geologic Energy Resources and Materials for the Energy Transition, Wednesday, 12 October 2022 – Geological Society of America Abstracts with Programs. Vol. 54, No. 5.

20 Lu Wang, Zhijun Jin, Xiao Chen, Yutong Su, Xiaowei Huang, 2023: The Origin and Occurrence of Natural Hydrogen - Energies 2023, 16(5), 2400; *https://doi.org/10.3390/en16052400*.

21 Lu Wang, Jiewei Cheng, Zhijun Jin, Qiang Sun, Ruqiang Zou, Qingqiang Meng, Kouqi Liu, Yutong Su, Qian Zhang, 2023: High-pressure hydrogen adsorption in clay minerals: Insights on natural hydrogen exploration - Fuel, Volume 344, 2023, p 127919, *https://doi.org/10.1016/j.fuel.2023.127919*.

22 Moretti, I., Geymond, U., Pasquet, G., Aimar, L., Rabaute, A., 2022: Natural hydrogen emanations in Namibia: Field acquisition and vegetation indexes from multispectral satellite image analysis - International Journal of Hydrogen Energy, Volume 47, Issue 84, 2022, Pages 35588-35607, ISSN 0360-3199, *https://doi.org/10.1016/j.ijhydene.2022.08.135*.

23 Hopwood, G., Links, F., 2024: *Reviewing Namibia's green hydrogen developments* - green hydrogen monitor, No1 Institute for Public Policy Research (IPPR), Windhoek, June 2024.

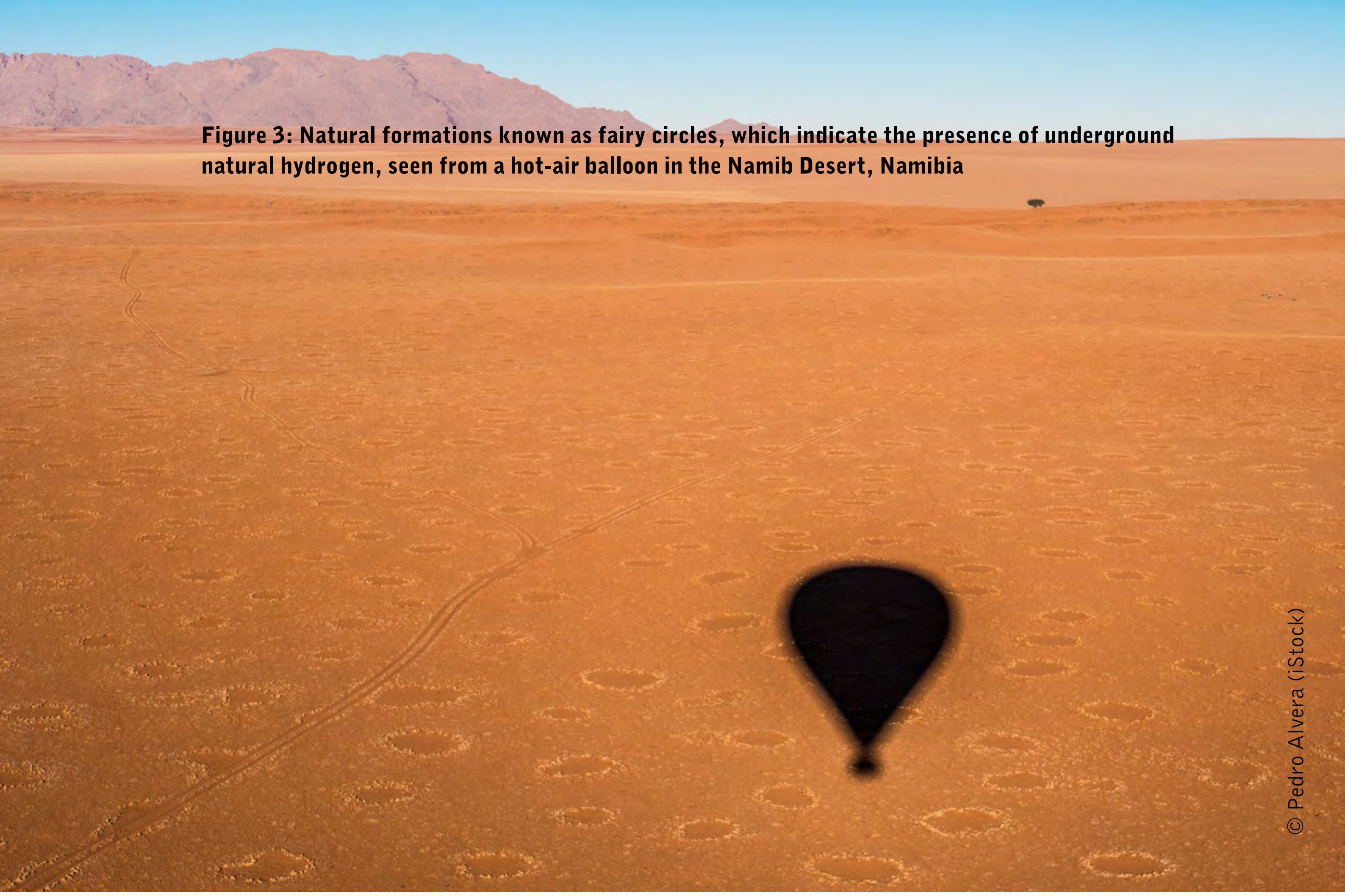


Figure 3: Natural formations known as fairy circles, which indicate the presence of underground natural hydrogen, seen from a hot-air balloon in the Namib Desert, Namibia

© Pedro Alvera (iStock)

Further afield, resources have been identified in Brazil[24], Australia[25], South Africa[26], South Korea[27], Japan[28], and in several other countries. None of these different deposits have been sufficiently explored to establish their economic viability.

24 Prinzhofer, A., Moretti, I., Françolin, J., Pacheco, C., D'Agostino, A., Werly, J., Rupin, F., 2019: Natural hydrogen continuous emission from sedimentary basins: The example of a Brazilian H2-emitting structure – International Journal of Hydrogen Energy, Volume 44, Issue 12, 2019, Pages 5676-5685, ISSN 0360-3199, *https://doi.org/10.1016/j.ijhydene.2019.01.119*.

25 Government of South Australia, 2023: Energy and Mining website on «Natural hydrogen»: *https://www.energymining.sa.gov.au/industry/energy-resources/geology-and-prospectivity/natural-hydrogen*.

26 Geymond, U., Ramanaidou, E., Lévy, D., Ouaya, A., Moretti, I., 2022: *Can Weathering of Banded Iron Formations Generate Natural Hydrogen? Evidence from Australia, Brazil and South Africa-Minerals*, 2022, 12, 163. *https://doi.org/ 10.3390/min12020163*.

27 Collins, L., 2023: *Natural hydrogen found? - State-owned oil company analysing five sites across South Korea* – hydrogeninsight, *https://www.hydrogeninsight.com/production/natural-hydrogen-found-state-owned-oil-company-analysing-five-sites-across-south-korea/2-1-1429573*.

28 Ryuichi Sugisaki, Masahiko Ido, Hiroshi Takeda, Yumiko Isobe, Yoshimitsu Hayashi, Noriaki Nakamura, Hiroshi Satake, Yoshihiko Mizutani, 1983: Origin of Hydrogen and Carbon Dioxide in Fault Gases and Its Relation to Fault Activity – The Journal of Geology, Vol. 91, No. 3 (May, 1983), pp. 239-258.

Less Enthusiasm in Germany

The US Government, the French Government, the EU (as part of the European Green Deal and the Fit for 55 package) and many other industrial players, including the Bill Gates's Breakthrough Energy Ventures[29],[30] are committing large sums of money for the research and development of geogenic hydrogen. In contrast, German researchers and officials have been slow in accepting this new challenge and are very conservative in their assessment of this new energy source.

The **German National Hydrogen Strategy** of 2020[31] only contains one sentence on «white hydrogen»: «We are also assessing the opportunities that may arise with regard to natural hydrogen resources.» In the update to this strategy in 2023, natural **hydrogen is no longer mentioned**. The German Federal Institute for Geosciences and Natural Resources (Bundesanstalt für Geowissenschaften und Rohstoffe, BGR in Hannover) published its Energiestudie 2021(Energy Study; state of data June 2020)[32] and barely mentioned white hydrogen stressing the uncertainties over the potential. As late as 2022, the BGR[33] still ignored geogenic hydrogen completely. The Energiestudie 2023[34] does not even mention geogenic hydrogen anymore. Current German research activities concern the **storage** of hydrogen in different rock types, but very little is being done on the exploration or the extraction of geogenic hydrogen.[35] In a recent Handelsblatt article[36] (6.5.2024), a spokeswoman for the Federal Ministry of Education and Research (BMBF) stated: *«Even if natural reserves of hydrogen so far have been underestimated, these will in all likelihood only play a local role. It remains open in how far extraction in Europe or Germany can be made economically viable.»*

29 Cookson, C., 2024: Geologists signal start of hydrogen energy ‹gold rush› – *Financial Times, 18. Feb. 2024.*

30 Dokso, A., 2023: Bill Gates-Backed Startup Revolutionizes Geologic Hydrogen – H2 energy news, 21.07.2023.

31 Federal Ministry for Economic Affairs and Energy - Public Relations Division, 2020: *The National Hydrogen Strategy, June 2020, https://www.bmwk.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.pdf?__blob=publicationFile&v=6.*

32 Franke B., et al., BGR (ed.), 2021: *BGR Energiestudie 2021 – Daten und Entwicklungen der deutschen und globalen Energieversorgung*. – BGR, Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover, 2021.

33 Lutz, R., Franke, D., Bahr, A., 2022: *KLIMABILANZIERUNG DER WASSERSTOFFHERSTELLUNG* - Commodity TopNews – Fakten, Analysen, Wirtschaftliche Hintergrundinformationen - Herausgeber: Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover, September 2022.

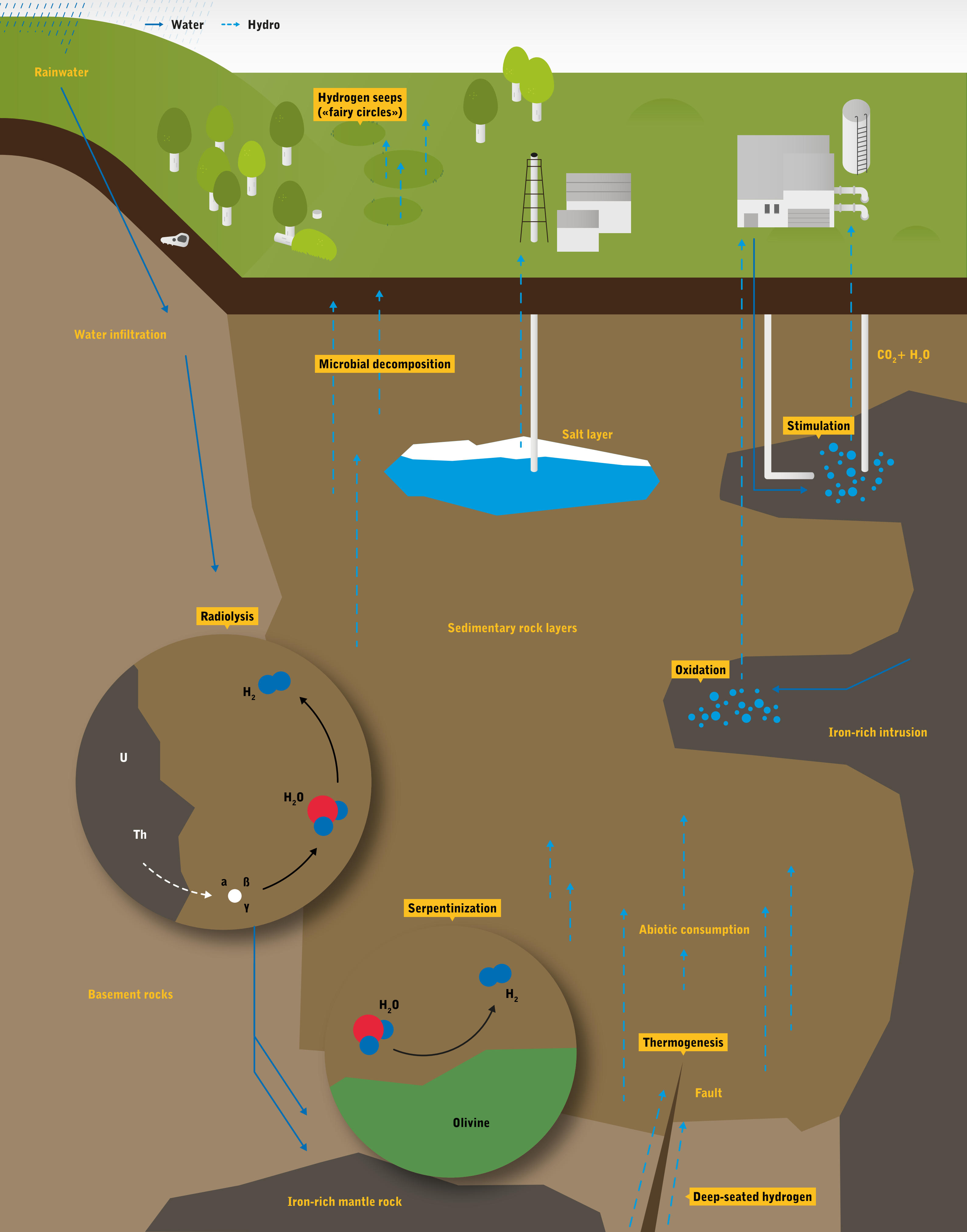
34 Blumenberg, M., et al., BGR (ed.), 2023: *BGR Energiestudie 2023 – Daten und Entwicklungen der deutschen und globalen Energieversorgung*.- BGR, Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover, 2023.

35 Bundesanstalt für Geowissenschaften und Rohstoffe, BGR (n. d.): Website: *https://www.bgr.bund.de/DE/Themen/Energie/Wasserstoff/wasserstoff_node.html;jsessionid=CFB71FDBAF426C9E09E1440AB17F76D5.internet951*.

36 Stratmann, K., 2024: Weißer Wasserstoff – mehr als nur ein Hoffnungsschimmer - Handelsblatt, 6.5.2024.

Figure 4: Earth's hydrogen factories

Hydrogen is a carbon-free fuel, but manufacturing it is dirty and expensive. Some researchers believe cheap, vast, and potentially renewable sources of natural hydrogen sit underground.



What is Geogenic Hydrogen and how is it generated

Our knowledge of the formation process of geogenic hydrogen is still scant. Much of it stems from the research into underground **hydrogen storage** as a crucial element of a new hydrogen-based energy system.

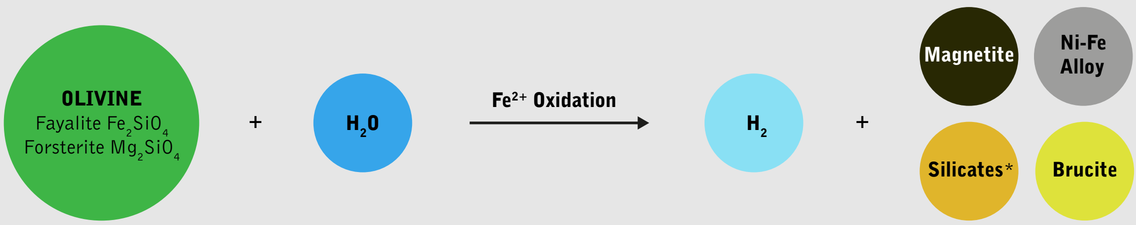
There are several **different geological processes**, that can lead to the formation of geogenic hydrogen. Several of these processes may actually interact in certain geological environments.

Serpentinization: very widespread and well-studied

Serpentinization is a common process of hydrothermal alteration of iron minerals in ultramafic rocks, such as peridotite, forming the mineral serpentinite, hence the name. In essence, the ubiquitous mineral olivine is altered to form serpentine, which is more stable and less dense. This process **releases heat and hydrogen gas** into the environment:

$2Fe_2SiO_4 + H_2O \rightarrow + 2SiO_2 + Fe_3O_4 + \mathbf{H_2}$ (simplified)

Figure 5: Serpentinization



*Crysolite, Lizardite & Antigorite, Talc, Chlorite, Si-rich phases

Source: Yedinak, 2022

This process occurs **when water interacts with the iron-bearing minerals in ultramafic rocks at temperature above 200 °C**, causing oxidation and the production of molecular hydrogen. Around 80% of the world's hydrogen sources are believed to derive from this process.[37] Most of the Earth's mantle is made of such ultramafic rocks, thus **hydrogen generation should be going on in large areas continuously**. The global quantities could be enormous.

37 Lamadrid, H., Rimstidt, J., Schwarzenbach, E., et al., 2017: *Effect of water activity on rates of serpentinization of olivine*. Nat Commun 8, 16107 (2017) - *https://doi.org/10.1038/ncomms16107*.

Radiolysis: Radioactive Decay of Minerals largely unknown

Radiolysis is the **decomposition of water molecules by natural radioactive decay** in minerals, producing hydrogen and oxygen. This process occurs at any temperature and pressure when radiation from elements such as uranium, thorium, and potassium interact with water, breaking the chemical bonds and releasing hydrogen. Radiolysis is an important source of hydrogen in geological environments, particularly in very deep subsurface settings where other hydrogen-generating processes like serpentinization might be limited.

Oxidation of Iron-bearing Minerals: well-studied, but limited

Oxidation refers here to a chemical reaction between water and iron-rich minerals in the Earth's crust[38]:

$Fe_2 + H_2O \rightarrow Fe_3 + OH^- + H_2$ (simplified)

When iron-rich minerals oxidize, they can split water molecules, generating hydrogen in the process. This mechanism is particularly relevant in environments where iron-rich minerals are exposed to water, contributing to the natural production of hydrogen in geological settings.

Microbial Decomposition of Organic Matter: well-studied, but limited

When microbes break down organic matter or other substrates in the absence of oxygen, the processes can release hydrogen as a byproduct. Such biological production of hydrogen can occur in various geological settings, including deep subsurface environments, hydrothermal vents, and sediment layers, adding to the overall geogenic hydrogen pool.

38 Waite, David, Miller, Christopher, Black, Emma, Feitz, Andrew, 2023: Hydrogen generation by subsurface iron mineral transformations (February 10, 2023). Proceedings of the Australian Hydrogen Research Conference 2023 (AHRC 2023) 8-10 February 2023, *http://dx.doi.org/10.2139/ssrn.4477913*.

Thermogenesis: Possible in Coal Fields

At high temperatures (over 400 °C) and pressure conditions, as they occur in deep geological layers, methane (MH4) can be thermally decomposed. Part of the methane can be broken down into molecular hydrogen and carbon compounds.

$CH_4 \rightarrow C + \mathbf{2H_2}$

In the so-called steam reforming this process is now technically used to produce «grey hydrogen» based on natural gas.

$CH_4 + H_2O \rightarrow CO + \mathbf{3H_2}$

It is still unclear whether this is a major contributor to hydrogen generation in the Earth.

Mechanoradical Hydrogen Generation

A more outlandish source of subsurface hydrogen has been noted in earthquake faults in Japan.[39]

«Hydrogen appears, almost everywhere, as a renewable source of energy, not a fossil one,» says the Brazilian researcher Alain Prinzhofer.[40] All these processes are continuously ongoing, often very fast, taking days or weeks, not millions of years as in the formation of fossil fuels like coal, oil, and gas. Due to the distinct physiochemical properties of hydrogen gas, natural hydrogen has a short residence time and suffers from many biotic and abiotic reactions consuming hydrogen itself.

Theoretically, geogenic hydrogen could be a renewable resource as it is continuously produced by geological forces all over the world. This would mean, that the search for host rocks and trap structure is not essential, if it is possible to tap directly into these formations where hydrogen generation is happening continuously. The boreholes in Mali have now released hydrogen continuously over more than 10 years without reduction of the gas flow. Thus, there are substantial differences (and less similarities) between natural gas and natural hydrogen. The industry needs to rethink its exploration strategies. Hydrogen is different. It is not just another «natural gas».

39 Hirose, T., Kawagucci, S., Suzuki, K., 2011: Mechanoradical H2 generation during simulated faulting:Implications for an earthquake-driven subsurface biosphere; 2011 - Geophysical Research Letters, VOL. 38, L17303, doi:10.1029/2011GL048850.

40 Hand, E., 2023: Hidden Hydrogen - Does Earth hold vast stores of a renewable, carbon-free fuel?- *Science, 17 FEBRUARY 2023 • VOL 379 ISSUE 6633.*

Geogenic hydrogen as a renewable resource

Geogenic hydrogen is particularly unstable and can react in many ways with other minerals, with water or organic matter along the way from its source to the surface. It is therefore rare to find large concentrations of hydrogen close to the surface. Usually, one has to drill into the source rock as closely as possible. Unfortunately, molecular hydrogen can react with carbon dioxide to form methane[41], thus adding to greenhouse gas (GHG) emissions in its extraction.

Geologists have long thought the tiny hydrogen molecule is **too small to efficiently be trapped** in host rocks and trap structures as they are required for the economic concentration of oil and gas in the earth. But what they did not consider is the **permanent and fast generation of hydrogen**. If it could be managed to tap into these continuous processes by drilling into the generation zone or a fracture zone, where hydrogen rises to the surface, one could capture hydrogen while it is being generated and there would be no need for a trap structure. The current cases in Mali and Albania all point in this direction.

In places where hydrogen is generated by the **oxidation of iron-rich minerals**, this opens even the possibility of **stimulating the hydrogen production** by injecting water into the underground. The first large-scale trial is currently prepared in the Samail ophiolite in Oman[42], just South of Muscat, by an American company, using its fracking experience and technology[43].

What is important to know is, that geogenic **hydrogen practically never exists in its pure form** as 100% hydrogen. Depending on the mineralogy of the source rock, it is almost always contaminated with other chemicals, notably hydrogen sulphide (H_2S) and methane. It is often also associated with helium (He).

41 Ranaee, E., Inzoli, F., Riva, M., Guadagnini, A., 2024: *Quantification of uncertainty related to methane production associated with geogenic hydrogen and carbon dioxide*, EGU General Assembly 2024, Vienna, Austria, 14–19 Apr 2024, EGU24-7879, *https://doi.org/10.5194/egusphere-egu24-7879, 2024*.

42 Neal, C., Stanger, G., 1983: Hydrogen generation from mantle source rocks in Oman - Earth and Planetary Science Letters, Volume 66, 1983, Pages 315-320, ISSN 0012-821X, *https://doi.org/10.1016/0012-821X(83)90144-9*.

43 businesswire, 2024: Eden-Announces-1.4-Million-in-ARPA-E-Awards-to-Develop-Stimulated-Geologic-Hydrogen-Technologies, businesswire, 13.2.2024, *https://www.businesswire.com/news/home/20240213921002/en/Eden-Announces-1.4-Million-in-ARPA-E-Awards-to-Develop-Stimulated-Geologic-Hydrogen-Technologies*.

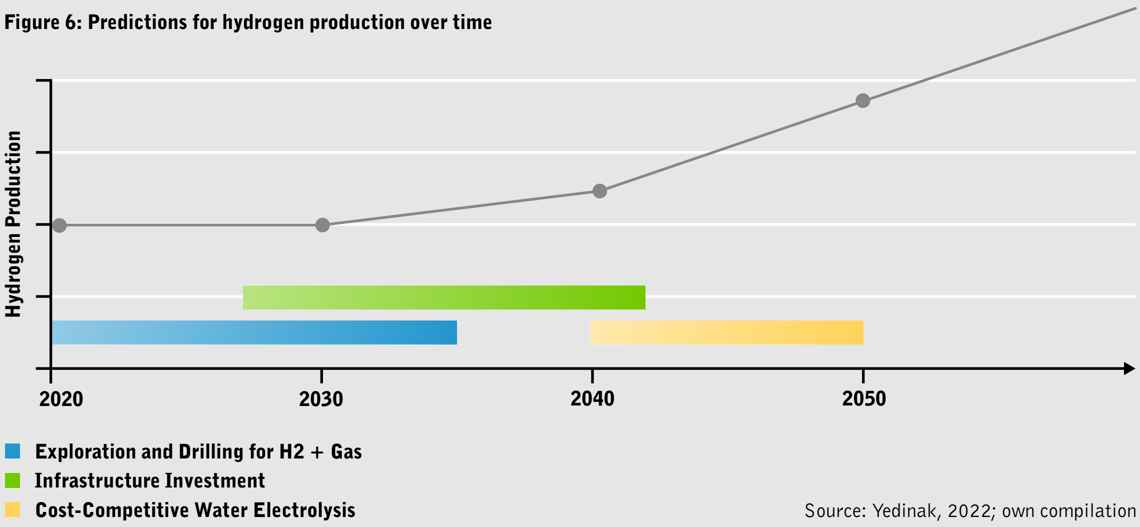
Potential Cost of Geogenic Hydrogen – and its Timing

Due to the few examples where geogenic hydrogen is actually captured, the estimation of the potential cost of geogenic hydrogen is difficult. Some sources in the industry claim that it can be produced cheaper than through the technical production of hydrogen.

Canada-based producer Hydroma is already extracting geogenic hydrogen (albeit in small quantities) at an estimated cost of $0.5 per kilogram. Projects in Spain and Australia are aiming for a cost of about $1 per kilogram. If these numbers are confirmed, it would demonstrate the **price competitiveness** of geogenic hydrogen[44].

Perhaps the **biggest drawback** for a meaningful contribution of geogenic hydrogen to the decarbonization of industry **lies in the timing**. Geogenic hydrogen is not a near-term solution. Any sizeable amount of geogenic hydrogen may not be available before 2040[45] and thus far too late to have an impact on reaching climate change targets. By then, cost-effective electrolysis of water will probably produce hydrogen cheaper than the predictions are for geogenic hydrogen. The Boston Consulting Group's Center for Energy Impact (CEI) takes a cautious but slightly more optimistic view[46].

Figure 6: Predictions for hydrogen production over time



Source: Yedinak, 2022; own compilation

44 Dokso, A., 2024: Numbers of Companies Searching for Natural Hydrogen Increases - H2 energy news, 18. 03. 2024.

45 Yedinak, Emily M., 2022: *The Curious Case of Geologic Hydrogen: Assessing its Potential as a Near-Term Clean Energy Source* - Joule 6, 503–508, March 16, 2022, Elsevier Inc.

46 Brijs, T., Berns, M., Merchant, W., Geerinck, J., Van Praet, B., Hirschhorn, P., Holm M., Goovaerts, S., 2024: *Beyond the Buzz: How Geological «White» Hydrogen Fits in the Low Carbon Hydrogen Puzzle* – Boston Consulting Group, Center for Energy Impact, May 2024.

Environmental Considerations

Several potential environmental impacts and climate change issues associated with geogenic hydrogen extraction can been identified.

While fugitive emissions from other parts of the hydrogen value chain have been studied in detail[47][48][49], there are only few studies dealing specifically with the possible increase in harmful emissions from the production and handling of geogenic hydrogen.

There are potential greenhouse gas leaks **all along the value chain of geogenic hydrogen**, starting with compromised well integrity right through to pipeline leakages.

Brandt (2023) has produced some «first estimates» of the greenhouse gas intensity of producing geogenic hydrogen[50], based on a model life cycle assessment (LCA).

In this initial life cycle assessment (LCA) for geogenic hydrogen he finds that the carbon footprint of geogenic hydrogen ranges from 0.5 to 5 kg carbon dioxide equivalent (CO2e) per kilogram of hydrogen, depending on initial gas concentrations and the methods of waste management like flaring or reinjection waste gas components, and the management of fugitive emissions. Even in worst-case scenarios with higher methane leakage and lower filtration efficiency, the carbon footprint remains lower.

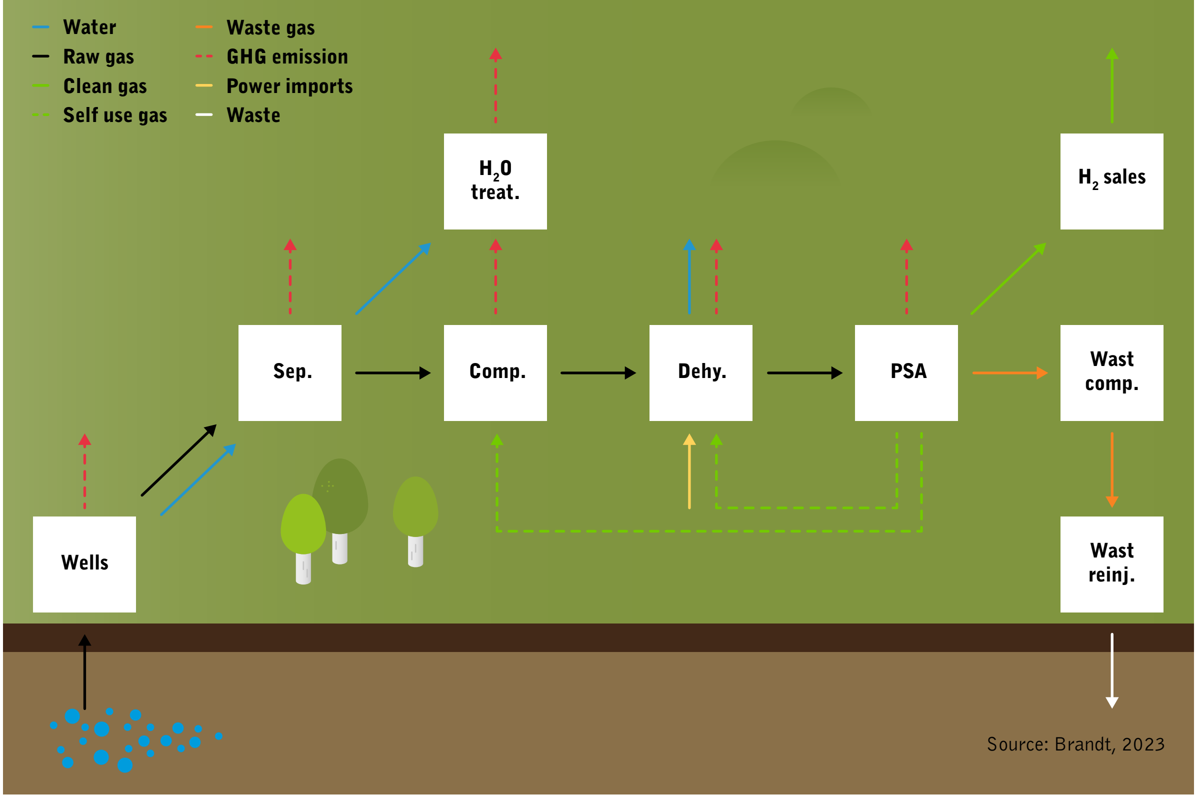
47 Alhamdani Y. A., et al., 2017: *The estimation of fugitive gas emissions from hydrogen production by natural gas steam reforming*, International Journal of Hydrogen Energy, 2016: *http://dx.doi.org/10.1016/j.ijhydene.2016.07.274*.

48 Dutta, I., Rajesh Kumar Parsapur, Sudipta Chatterjee, Amol M. Hengne, Davin Tan, Karthik Peramaiah, Theis I. Solling, Ole John Nielsen, Kuo-Wei Huang, 2023: *The Role of Fugitive Hydrogen Emissions in Selecting Hydrogen Carriers* - ACS Energy Lett. 2023, 8, 7, 3251–3257*https://doi.org/10.1021/acsenergylett.3c01098*.

49 Frazer-Nash Consultancy, 2022: *Fugitive Hydrogen Emissions in a Future Hydrogen Economy* - FNC 012865-53172R Issue 1.

50 Brandt, A. R., 2023: *Greenhouse gas intensity of natural hydrogen produced from subsurface geologic accumulations*, Joule, Volume 7, Issue 8, 2023, Pages 1818-1831, ISSN 2542-4351, *https://doi.org/10.1016/j.joule.2023.07.001.*

Figure 7: Greenhouse gas intensity of natural hydrogen produced from subsurface geological accumulations



Source: Brandt, 2023

Despite the potential of geogenic hydrogen to contribute to the decarbonization of industry, particularly in the transport sector, there are **substantial risks associated with its extraction process**.

– Hydrogen is highly fugitive, and **leaks are therefore much more common** than in natural gas production.

– There are a number of **associated gases**, sometimes in large quantities, which need to be managed carefully because of their toxic and explosive characteristics and greenhouse gas footprint.

– Hydrogen itself and its associated gases are **substantial greenhouse gases**.

– As of now, there are no up-to-date published life **cycle assessments of geogenic hydrogen**.

– Drilling and gas treatment infrastructure **may have a huge impact on the environment and on host communities**.

A) Hydrogen leaks

As a very small molecule, hydrogen is much more prone to leakage than other gases, for example natural gas. When released into the atmosphere, hydrogen can increase the concentration of methane and ozone in the troposphere by interfering with the atmospheric chemistry, that breaks down methane. It is colorless, odorless, and tasteless, making it difficult to detect without specialized equipment. **Increased extraction of hydrogen from geological resources will increase the fugitive emissions of it to the atmosphere**. More exploration for hydrogen and transportation by pipelines will increase the risk of undetected leaks. Hydrogen can cause embrittlement in some metals, making them more prone to cracking and failure. **This material degradation can compromise the integrity of pipelines, valves, joints, etc., thus requiring a much closer leak monitoring than in conventional gas infrastructure**. Development and deployment of sensitive detection systems, such as sensors and continuous monitoring systems, are essential to quickly identify and address hydrogen leaks, including the implementation of specialized well-protection protocols.

B) Associated gases

Economic exploitation of geogenic hydrogen requires at least 60% of the sampled gas to be hydrogen. In many hydrogen systems to date, its content is often below 40%. Few flow test results have been published so far:

- **Bourakébougou in Mali** has consistently shown over 90% hydrogen, with sometimes 98% hydrogen, 1% methane, and 1% nitrogen.
- The hydrogen source in **Bulqizë in Albania** is not fully analyzed and published yet.
- **Australian boreholes on Kangaroo Island** have shown 70-80% hydrogen, with the remainder being carbon dioxide and methane.
- The **Nebrasca well of Koloma** has discovered flows of hydrogen with a purity of up to 86%, and up to 6.8% of helium.
- Other hydrogen percentages have been reported: Turkey 12%; Iceland 24%; Japan 51%; Oman 82%; and in the USA with up to 96%.

Associated gases are therefore often co-produced in large quantities. It is of course possible to produce pure hydrogen by separating the hydrogen from the associated gases, but the **effectiveness and cost structure** of membrane separation have not yet been evaluated.

Associated gases are predominantly:

- **methane** (and other hydrocarbons like ethane, propane, and butane), and
- **carbon dioxide**.

Lower volumes are reported of:

- **hydrogen sulphide**,
- **nitrogen**,
- **helium** and other noble gases like neon, argon, krypton and xenon.

Of these, hydrogen sulphide is of particular interest as it is highly toxic even in very low concentrations, whereas the other associated gases have to be reviewed for their greenhouse gas intensity.

Box3: What are the main associated gases?

Methane CH_4: Methane (and other hydrocarbons like ethane, propane, and butane) is found in varying proportions, ranging from a few parts per million (ppm) to several per cent by volume. In some cases, methane can be the dominant gas, especially in environments, where organic matter is present and undergoing thermal decomposition (as in coalbed methane). Methane is produced by both, biological processes (biogenic) and geological processes (thermogenic). Its presence can indicate the breakdown of organic material or abiotic reactions, involving carbon-containing minerals. Its GHG potential is well established. If vented or flared at source – as it is still often the case in remote natural gas systems, methane could tip the balance for the carbon-neutrality of geogenic hydrogen. The process by which petroleum forms from organic-rich rocks consumes any available hydrogen (methanogenesis). This is one of the reasons why hydrogen is rarely found with larger amounts of hydrocarbon gases, like methane or propane.[51] Production of hydrogen from poor-quality reservoirs or deep-buried coals may require fracking or other forms of well stimulation, bringing about further environmental concerns.

Carbon dioxide CO_2: Higher values of carbon dioxide are reported from hydrogen sources, that are believed to originate from magma degassing[52]. Its GHG potential is well established.

51 Ellis, G., 2023: USGS: The Potential of Geologic Hydrogen for Next-Generation Energy - A previously overlooked, potential geologic source of energy could increase the renewability and lower the carbon footprint of our nation's energy portfolio: natural hydrogen - Website Central Energy Resources Science Center, United States Geological Survey (USGS): *https://www.usgs.gov/news/featured-story/potential-geologic-hydrogen-next-generation-energy*.

52 Daskalopoulou, K., Gagliano, A. L., Calabrese, S., et al., 2019: *Degassing at the Volcanic/Geothermal System of Kos (Greece): Geochemical Characterization of the Released Gases and CO2 Output Estimation* – Hindawi Geofluids, Volume 2019, Article ID 3041037, 16 pages, *https://doi.org/10.1155/2019/3041037*.

Hydrogen sulphide H_2S: As a greenhouse gas, hydrogen sulphide is less effective than carbon dioxide or methane. Due to its low concentration and short lifespan, its contribution to the greenhouse effect is minimal. High concentrations of hydrogen sulphide are toxic to humans and animals, causing respiratory issues and even death in extreme cases. Its environmental impact includes corrosion of infrastructure and contribution to air pollution. It degrades into sulfur dioxide, which can lead to the formation of sulfate aerosols. These have a cooling effect on the climate by reflecting sunlight away from the Earth.

Nitrogen N_2: Molecular nitrogen is very stable and does not absorb infrared radiation, which means it does not contribute directly to the greenhouse effect. When hydrogen is used as heat source for energy generation, larger amounts of nitrogen oxides (NOX) are produced, thus adding to the formation of particulate matter (PM) and aerosols. These aerosols have complex effects on climate by influencing cloud formation and altering the Earth's radiation balance.

Helium He: Helium and other noble gases like neon, argon, krypton, and xenon are primarily produced through the radioactive decay of heavy elements such as uranium and thorium within the Earth's crust. They are thus more prevalent in hydrogen sources due to radiolysis. The greenhouse effects of these noble gases are minimal. Instead, they could be valuable byproducts and could add to the financial viability of geogenic hydrogen extraction.

C) The net greenhouse effect of geogenic hydrogen production

Hydrogen itself is not a greenhouse gas. But it has an indirect impact on climate change. When released into the atmosphere, hydrogen can increase the concentration of methane (a potent greenhouse gas) and ozone in the troposphere by interfering with the atmospheric chemistry that breaks down methane.

Hydrogen's short-lived atmospheric warming effects, which last only a couple of decades (+_40 years) , are often underestimated by standard climate impact assessments that focus on long-term effects of a single emissions pulse, masking hydrogen's stronger near- to medium-term warming potency, especially concerning due to hydrogen's tendency to leak into the atmosphere and the unknown total emissions from current hydrogen systems.[53]

53 Ocko, Ilissa B., Hamburg, Steven P., 2022: *Climate consequences of hydrogen emissions* - Atmospheric Chemistry and Physics, Volume 22, issue 14, p. 9349–9368, 2022 - *https://doi.org/10.5194/acp-22-9349-2022*.

D) Local environmental effects

The production of geogenic hydrogen may have several potential local environmental impacts at the extraction site. They are mostly similar to other projects when drilling for natural gas exploration and production:

- **land disturbance from exploration and drilling**,
- **water usage and contamination**,
- **emissions from pipelines and handling**,
- **induced seismic activity**.

In particular, water requirements for drilling and maintaining the infrastructure might become problematic for local populations in water-stressed areas. Mitigating these environmental impacts requires careful planning, adherence to regulations, and the implementation of best practices in environmental management.

One particular threat is the embrittlement of steel pipes, valves, and fittings by the continued exposure to hydrogen, leading to earlier **equipment failure** and **reduced well integrity**.

Potential for Co-Generation in Enhanced Geothermal Systems (EGS)

There is currently very little research dedicated to the potential of **co-generation of geogenic hydrogen in** enhanced **geothermal energy systems**. Most geothermal systems contain sizeable amounts of hydrogen, which can be separated at low cost in installations already existing. The only case where this could be done on an industrial scale and under favorable economic conditions is reported from Iceland[54]. There, the hydrogen is currently just emitted into the atmosphere but could be recovered and utilized. Turkey[55] is another country with a substantial potential to integrate hydrogen recovery into its widespread

54 Combaudon, V., Moretti, I., Kleine, B.I., Stefánsson, A., 2022: Hydrogen emissions from hydrothermal fields in Iceland and comparison with the Mid-Atlantic Ridge. International Journal of Hydrogen Energy, 47 (18), pp.10217–10227.

55 Kubilay Karayel, G., Javani, Nader, Dincer, Ibrahim, 2022: Effective use of geothermal energy for hydrogen production: A comprehensive application - Energy, Volume 249, 2022, 123597, ISSN 0360-5442, *https://doi.org/10.1016/j.energy.2022.123597*.

geothermal energy systems. Australia[56] has low-temperature geothermal reservoirs, in particularly hot sedimentary aquifers with a high potential for co-generation of geothermal heat (and electricity) with hydrogen recovery.

56 Hamlehdar, M., Beardsmore, G., Narsilio, G.A., 2024: Hydrogen production from low-temperature geothermal energy - International Journal of Hydrogen Energy, Volume 77, pp. 742-768, *https://doi.org/10.1016/j.ijhydene.2024.06.104*.

Major Unknowns in Geogenic Hydrogen

Research and exploration for geogenic hydrogen is still in its infancy. Thus, major unknowns limit our understanding and are harnessing this process effectively. Here are some of the key unknowns:

- **Production figures:** There is still a **huge uncertainty** about the potential production figures of geogenic hydrogen. However, most estimates see the possible production at least one or two orders of magnitude smaller than the demand figure of the International Energy Agency (IEA).
- **Quantification of resources:** The global distribution and quantity of geogenic hydrogen resources are **not well understood**. Estimates of hydrogen production rates and accumulations in different geological settings (e.g. mid-ocean ridges, continental crust, peridotite bodies) vary widely. There is a need for reliable methods to prospect for and measure hydrogen fluxes and concentrations in different geological settings.
- **Production mechanisms:** While processes like serpentinization and radiolysis are known to produce hydrogen, the detailed reaction pathways, rates, and influencing factors are **not fully understood**. The kinetics of hydrogen-producing reactions under various temperature, pressure, and chemical conditions need further investigation.
- **Sustainability and renewability:** The long-term sustainability of hydrogen **production from geological processes is uncertain**. Determining whether these sources can provide a continuous hydrogen supply over extended periods in areas accessible to the main markets is critical. Understanding how quickly hydrogen accumulations can be depleted and how they might be replenished over geological timescales is important.
- **Technological challenges:** Developing efficient and cost-effective methods for exploring and extracting geogenic hydrogen is happening only now, with uncertain results and fierce competition. This includes drilling technologies, sampling methods, and the development of appropriate sensors. Judging from past experiences in the natural gas sector, it can take a decade or longer to bring a «hydrogen field» into production, as every deposit and hydrogen source is different. Addressing the challenges of storing and transporting hydrogen, especially from remote or deep-sea locations, has not even started.
- **Economic viability:** Feasibility of extracting geogenic hydrogen compared to other sources of hydrogen, such as electrolysis of water or steam methane reforming, remains open. The potential market demand for geogenic hydrogen and its competitiveness with other energy sources depend on the timing when hydrogen sources become productive.
- **Environmental impact:** The potential environmental impact of large-scale geogenic hydrogen extraction on local ecosystems, groundwater systems, and the atmosphere

has not yet been studied. Based on the ecologically destructive experiences of other energy sources such as oil and gas, it is crucial to understand the environmental and social risks before going into the extraction of new energy sources to avoid fueling the climate crisis further and strengthening lock-in effects.

- **Regulatory and legal framework:** Developing appropriate regulatory frameworks and guidelines for the exploration, extraction, and commercialization of geogenic hydrogen will differ substantially from those of the natural gas sector.

Addressing these unknowns requires coordinated research efforts, advancements in technology, and collaboration across multiple scientific and industrial disciplines.

Summary

1. Geogenic hydrogen has been **known for a long time but has not been** – for a number of scientific reasons – **considered a relevant resource**. This perception has only changed over the last 3–4 years, a timeline too short to allow yet for a meaningful more in-depth analysis of the long-term potential.
2. Only in the last few years researchers have begun to evaluate geogenic hydrogen **sources all over the world**. In only very few cases there is a sound understanding of the underlying mechanisms for geogenic hydrogen generation and still a first order of magnitude resource assessment.
3. **Serpentinization is by far the most prevalent generation process**. It takes place continuously and over large tracks of the Earth. It is most likely a ubiquitous, renewable resource, where host rocks (reservoirs) and cap rocks or trap structures are less relevant than in the traditional natural gas industry.
4. **The underlying chemistry behind geogenic hydrogen is simple**. Various iron minerals change their oxidation status in contact with water consuming its oxygen and releasing hydrogen in the process. As iron is nearly ubiquitous in most rock formations, the potential for hydrogen generation is potentially unlimited.
5. Nonetheless, geogenic hydrogen is **hard to find** (as we do not fully understand its formation process) and easy to lose as it is too small to be contained in most geological traps and reacts quickly with other substances in the earth.
6. **The biggest problem perhaps is the geographical distribution**. It is mostly unknown, theoretically widespread, but certainly far from the natural gas infrastructure and far from the markets. The USGS is producing an interactive map of prospectivity areas in the US. In the EU there is high potential in the Pyrenees and in the European Alpes. Australia is another potential source area for geogenic hydrogen.
7. An essential question is **what it will cost to produce geogenic hydrogen**. A first modelling of the cost structure by the USGS and market claims of less than 1 US$/kg make it immediately competitive with the industrial production of hydrogen.
8. **Yet, markets are interested**. Some large companies spend millions on research and resource identification.
9. At the current production rate, **geogenic hydrogen will not play an important part** in combatting climate change nor in the emerging hydrogen markets.
10. Large-scale production of natural hydrogen for the global market is **unlikely to happen before the period of 2035–2040**.
11. Most probably, it will ***come too late and too little*** for a larger share in the hydrogen mix. But **even if it is only 5%** of the global hydrogen demand, it might be worthwhile

testing and looking more closely at a **potentially unlimited, low-cost and low-carbon resource**.

12. As a naturally occurring energy source, geogenic hydrogen does have the **potential to play a certain role in the energy transition**. However, it is not going to be a silver bullet and will not replace other efforts for decarbonization.

13. In the field of hydrogen technologies, knowledge and **technology grows very fast**. As basic concepts evolve, new technologies are tried. This year a trial starts in Oman on the first **experiment to stimulating a hydrogen well**.

14. The EU should **continue to support research and development in this area**, while also setting **strict regulations** to prevent the negative consequences, that have plagued other extractive industries. There is a need to extend the international certification schemes for hydrogen as a low-carbon or carbon-free fuel to geogenic hydrogen.

Glossary

Carbon dioxide equivalent (CO_{2e} or CO_2-eq) is as a metric measure used to compare the emissions from various greenhouse gases on the basis of their global warming potential, by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential. It is commonly expressed as million metric tonnes of carbon dioxide equivalents.

Carbon footprint: A carbon footprint is a calculated value or index used to compare the total amount of greenhouse gases emitted directly or indirectly into the atmosphere e.g. by a process, product, company or country. Carbon footprints are usually expressed as tonnes of carbon dioxide equivalents per unit of comparison.

Enhanced geothermal energy systems (EGS) generate geothermal electricity from the deep subsurface independently of water-bearing horizons. Essentially, the energy stored in the hot, low-permeability rock is utilised by creating or expanding a heat exchanger at depth through stimulation.

Fairy circles are natural circular depressions, that seep hydrogen from their perimeters and have been found on places across the globe, e.g. in Australia, Namibia, Mali, Brazil, the United States, and Russia.

Greenhouse gas intensity is the emission rate of greenhouse gases relative to the energy produced, expressed in grams of carbon dioxide equivalents per megajoule of energy produced (gCO_{2e}/Mj).

Ophiolites are pieces of oceanic crust (and upper mantle) that have been uplifted onto the edge of continental plates. They are an assemblage of mafic and ultramafic lavas and hypabyssal rocks sometimes found in association with sedimentary rocks. Ophiolites have been found in Cyprus, New Guinea, Newfoundland, California, and Oman.

Peridotite is the dominant coarse-grained rock type of the upper part of Earth's mantle, consisting predominantly of the mineral olivine.

Serpentinization is a slow metamorphic process of transformation of olivine and pyroxene into serpentinite. Reaction rates can vary significantly depending on factors such as temperature, pressure, water activity, and the composition of the rock. The speed of serpentinization can range from a few micrometers per year to several millimeters per year.

Steam reforming is the process, in which high-temperature steam (700°C–1 000°C) is used to produce hydrogen from a methane source, such as natural gas.

Troposhere is the lower part of the atmosphere, beginning at the Earth's surface and extending up to 6–20 kilometers high, where almost all weather occurs.

Ultramafic rocks are a type of igneous rocks that are very high in magnesium and iron (mafic) minerals. They have a very low silica content, typically less than 45% by weight. These rocks are predominantly composed of minerals, such as olivine, pyroxene, and amphibole, with very little feldspar or quartz.

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