The Search for Natural Hydrogen: A Hidden Energy Giant or an Elusive Dream?

Aliakbar Hassanpouryouzband[a*] , Timothy Armitage[b], Trystan Cowen[c], Eike M. Thaysen[d], Sean McMahon[a], Hadi Hajibeygi[e], David S. Stevenson [a], Morten Stahl[f], R. Stuart Haszeldine[a]

a) School of Geosciences, University of Edinburgh, Grant Institute, West Main Road, Edinburgh EH9 3FE, United Kingdom
b) British Geological Survey, The Lyell Centre, Research Avenue South, Edinburgh EH14 4AP, United Kingdom
c) Ove Arup and Partners Limited, Sheffield, S1 2JE, United Kingdom
d) Department of Geosciences, Institute of Environmental Assessment and Water Research (IDAEA), Spanish Council for Scientific Research (CSIC), Jordi Girona 18–26, 08034 Barcelona, Spain
e) Department of Geoscience and Engineering, Faculty of Civil Engineering and Geosciences, Delft University of Technology. Stevinweg 1, 2628CN, Delft, The Netherlands
f) Natural Hydrogen Ventures ApS, Jeppe Aakjaers Vej 2, 8230 Aabyhoej, Denmark

The Search for a Hidden Energy Giant

The idea of a vast, untapped reservoir of natural hydrogen[1], one that could transform global energy systems, is as enticing as it is elusive. If a substantial, economically viable hydrogen field exists and can be exploited with minimal leakage to the atmosphere, it would mark a paradigm shift, offering a relatively clean energy source with low operational emissions. Unlike fossil fuels, which require carbon-intensive extraction and combustion, or green hydrogen[2], which depends on large-scale renewable energy input, natural hydrogen could provide an energy supply that does not require conversion from electricity or fossil fuels, making it a potentially simpler and more continuous resource[3]. However, because hydrogen is an indirect greenhouse gas, any future exploitation must include robust monitoring strategies to quantify and minimise atmospheric losses in order to preserve its environmental advantages.

But there is a fundamental challenge: despite numerous documented hydrogen occurrences worldwide, no truly large-scale, commercially viable reserve has been found. This reality forces us to confront a crucial question, are we on the verge of discovering a new energy frontier, or will natural hydrogen remain a scientific curiosity[4] with limited economic impact?

To answer this, we must address two key uncertainties: Where should we look for a major natural hydrogen deposit? And what steps are needed to confirm its economic viability? The answer requires an exploration strategy that combines geological understanding, advanced detection techniques, and a willingness to take financial risks. If we fail to find a large reserve, alternative strategies, such as engineered subsurface hydrogen production (hydrogen farming[5]/stimulated hydrogen[6]), will become increasingly necessary, albeit at a higher cost.

A Widespread Phenomenon, but Not Yet an Economic One

Natural hydrogen seepages have been recorded across the globe, from the Bourakébougou field in Mali[7] to occurrences in Australia[8], the USA[9], and Europe[10] (Fig. 1). These sites confirm the existence of hydrogen-generating geological processes; yet no confirmed, large-scale reservoir has been identified. This raises the fundamental issue: why hasn't hydrogen accumulated in economic quantities? The answer likely lies in the short geological residence time of hydrogen. Unlike hydrocarbons, which can be trapped in subsurface reservoirs for millions of years, hydrogen is more diffusive and susceptible to losses through leakage and microbial consumption. However, recent work shows that under non-

* Corresponding Author: A.H: Hssnpr@ed.ac.uk

reactive conditions, caprocks that seal hydrocarbons are generally capable of sealing hydrogen as well, as hydrogen may support higher column heights than methane[11]. The challenge, then, is not merely detecting hydrogen, but finding geological systems capable of ensuring long-term retention and confinement of a high concentration of hydrogen molecules at relatively high pressures. For hydrogen to persist in the subsurface, its generation[12] must outpace losses. Subsurface production needs to reach a level where significant accumulations form, while effective trapping mechanisms are necessary to prevent diffusion over time. Equally important is the feasibility of economic extraction; deposits must be sufficiently large and accessible to justify commercial development. Hydrogen leakage also presents a challenge. Even if a subsurface system generates hydrogen at high rates, a range of losses may still prevent economic accumulation. Beyond resource viability, leakage carries environmental implications. Current estimates suggest that if atmospheric losses exceed approximately 10%, green hydrogen may offer no net climate benefit. Controlling leakage is therefore not only a technical necessity but also a climate imperative. Further research is needed to quantify these losses, assess their atmospheric effects, and develop strategies to minimise emissions. Without these conditions, hydrogen seepages remain scientifically valuable but commercially insignificant. However, this does not diminish their importance; these findings provide critical insights into subsurface hydrogen cycling and could guide the search for larger reservoirs.

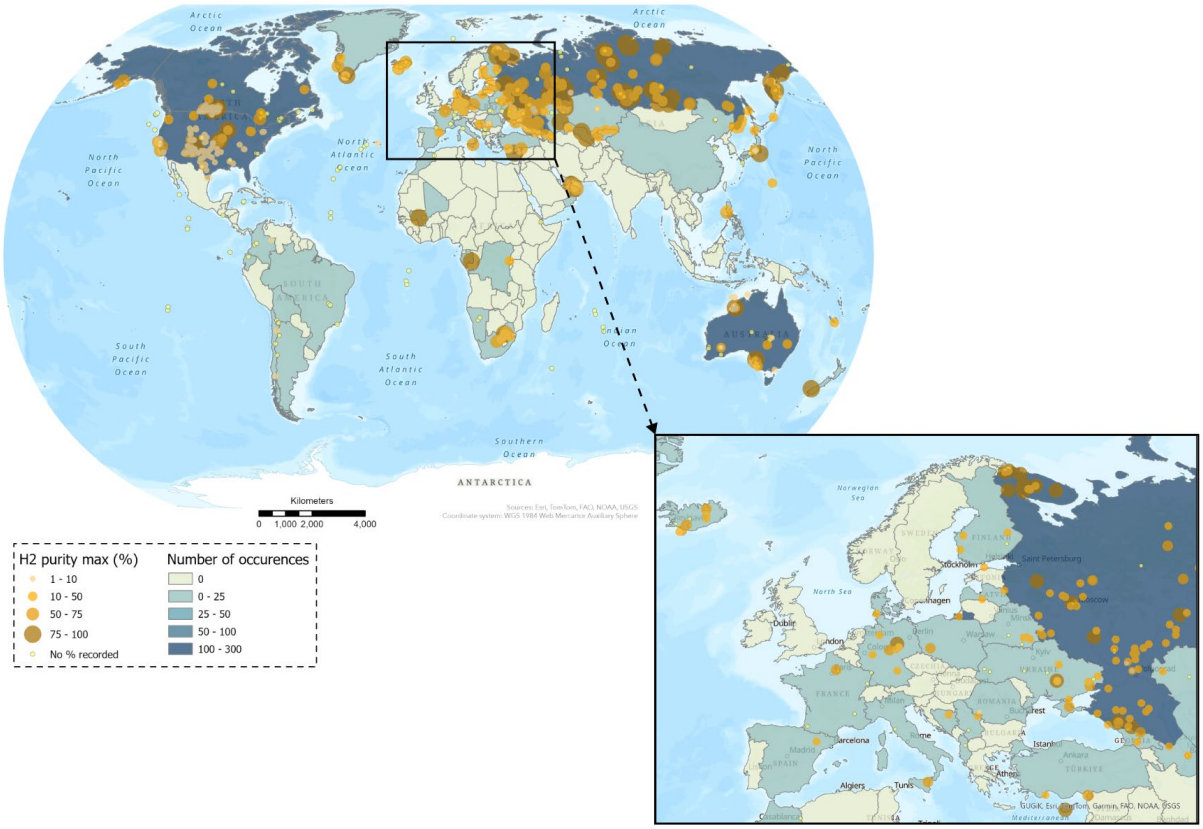

Fig. 1. Global distribution of natural hydrogen occurrences. *Documented hydrogen seepages and subsurface accumulations across diverse geological settings indicate widespread generation processes. The map highlights reported maximum hydrogen purity levels, with higher concentrations suggesting potential reservoirs. Despite these observations, no large-scale, economically viable hydrogen field has yet been confirmed. The variability in occurrence underscores the need for systematic exploration, improved detection methods, and targeted drilling to assess the feasibility of hydrogen as a natural energy resource. Data compiled from Esri, FAO, NOAA, USGS, and other sources.*

Where to Look: Geological Traps for Hydrogen Accumulation

If a major hydrogen field exists, it is most likely hidden in a geological trap[13] that has prevented its escape over geologic time. Similar to hydrocarbons, hydrogen requires sealed reservoirs to remain concentrated. Various structures may play a role in hydrogen accumulation, from anticlines and fault bounded reservoirs to salt domes[14] and sedimentary formations with permeability contrasts[15]. Fig. 2 provides a conceptual framework for different trap types that could be relevant for hydrogen retention. Some hydrogen may even be retained in cryogenic conditions or associated with hydrocarbon systems. However, the effectiveness of these trapping mechanisms in long-term hydrogen retention remains an open question. A detailed discussion of potential trapping mechanisms and sealing formations is provided in the Supporting Information (Table S1.).

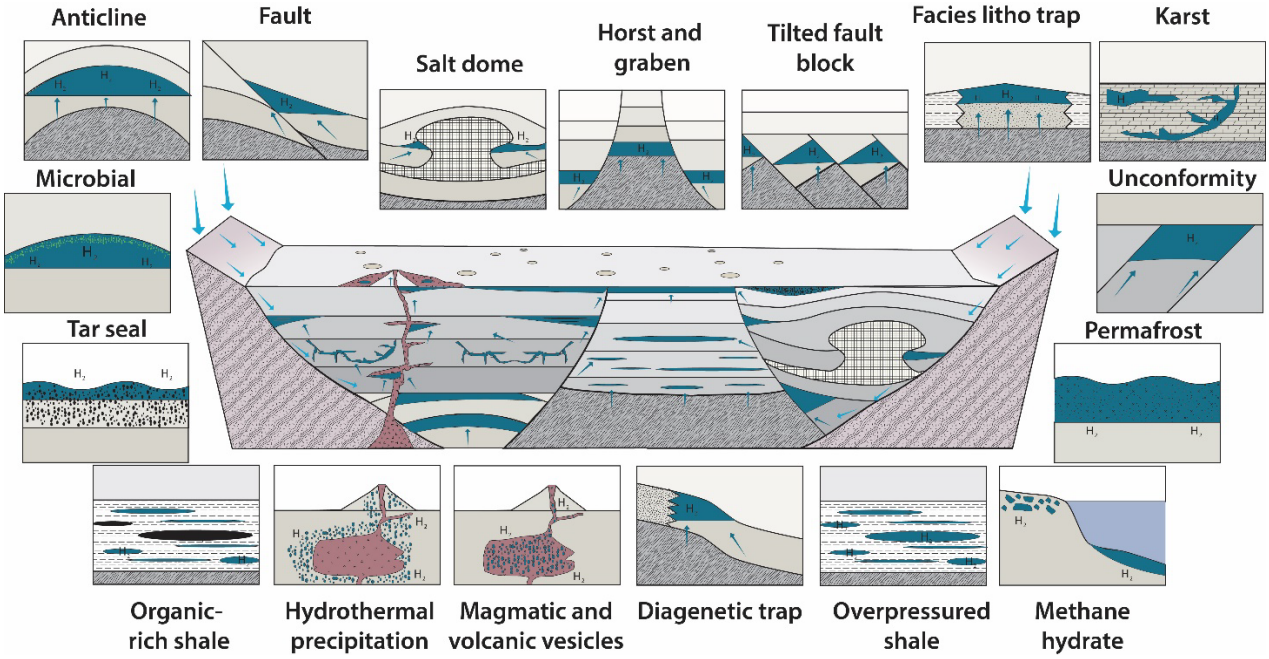

Fig. 2 Potential geological traps for natural hydrogen accumulations. *Hydrogen can accumulate in a variety of subsurface environments if effective sealing mechanisms prevent its escape. Structural traps, such as anticlines, faults, salt domes, horst and graben systems, and tilted fault blocks, may retain hydrogen within porous formations. Stratigraphic and sedimentological controls, including facies lithological traps, karst systems, and unconformities, can also influence hydrogen entrapment. Cryogenic and geochemical processes, such as permafrost barriers, methane hydrates, and overpressured shales, may provide additional sealing mechanisms. Hydrogen may also be associated with organic-rich shales, magmatic and volcanic vesicles, hydrothermal precipitation zones, and diagenetic traps. Understanding these varied trapping mechanisms is crucial for guiding future exploration and assessing the potential for large-scale hydrogen reservoirs.*

Some researchers argue that hydrogen fields may require specific conditions to remain stable[16]. High temperatures, for instance, could limit microbial consumption and prolong hydrogen retention. Alternatively, deep-seated overpressured systems could prevent diffusion, though the role of these factors remains speculative. Identifying and characterizing real-world examples of effective hydrogen traps will be crucial for advancing exploration. Despite the theoretical potential of these systems, direct testing is required to assess whether they can effectively store and retain hydrogen over geologic timescales. To date, the lack of dedicated deep hydrogen exploration wells[17] remains a significant limitation in confirming these hypotheses, although a few recent projects have begun to focus specifically on deep hydrogen exploration. Equally important is that most existing oil and gas wells lack

the necessary detection equipment to identify hydrogen, meaning many potential occurrences may have gone unnoticed.

The Path to Discovery: Steps Toward Identifying a Major Hydrogen Field

If natural hydrogen is to emerge as a viable energy resource, regulations, science and investment must advance towards a faster issuing of drilling licenses, a larger capital spending and an elucidation of the geological and biogeochemical conditions that grant maximum hydrogen accumulation, respectively (Fig. 3).

Fig. 3 Key elements required for the discovery of a large natural hydrogen field. *The successful identification of an economically viable hydrogen reservoir depends on the interplay between scientific research, regulatory frameworks, and financial investment. Advancing geological and geochemical understanding is essential for predicting regions with high hydrogen generation and accumulation potential. Large-scale investment is necessary to fund exploration, including geophysical surveys and deep drilling campaigns. Simplified regulatory procedures are required to facilitate hydrogen exploration and ensure that promising sites can be assessed without excessive delays. These interconnected factors must align to enable the discovery of a significant natural hydrogen field.*

Regulatory frameworks must be adapted to facilitate hydrogen exploration, as many regions still lack clear legal pathways for permitting and licensing. Without regulatory support, even promising discoveries may face unnecessary delays. At the same time, large-scale investment is essential, as drilling for hydrogen carries inherent risk. Unlike the well-established hydrocarbon sector, hydrogen exploration requires capital willing to embrace uncertainty, as multiple unsuccessful wells may precede a breakthrough discovery.

Beyond policy and investment, the scientific approach must advance as well. Geological surveys must be expanded, utilizing advanced hydrogen detection techniques such as high-resolution spectrometry and subsurface imaging to identify potential hydrogen-rich basins. However, surface measurements alone are insufficient; deep drilling campaigns must be undertaken to test whether substantial

reservoirs exist at depth. Hydrogen may also be present as dissolved gas[18] in formation brines, detectable only after the fluids are brought to the surface and the gases released for analysis, typically via gas chromatography. As such, only by moving beyond existing theoretical models and shallow seepage studies, techniques, and practices can we confirm whether large-scale hydrogen accumulations are indeed a reality.

Even if a discovery is made, further steps are required to assess its viability. Measuring hydrogen leakage rates and evaluating the integrity of potential seals will determine whether an accumulation can be exploited over the long term. The difference between an isolated hydrogen pocket and a sustainable resource lies in whether the gas can remain trapped at useful concentrations. Without bold investment and exploration efforts, hydrogen's economic potential will remain theoretical.

If the Big One Doesn't Exist, What Then? Hydrogen Farming as a Backup

If large natural hydrogen fields are never found, the alternative is to engineer hydrogen generation within the subsurface, a process often referred to as hydrogen farming. This involves artificially stimulating water-rock reactions[19] underground to produce hydrogen, mimicking natural generation processes in controlled and enhanced reactive environments. Another emerging approach involves in situ hydrogen generation from fossil hydrocarbon reservoirs[20]. This method relies on injecting steam or oxidants to stimulate subsurface thermochemical reactions such as steam reforming, partial oxidation, or gasification. In this process, the majority of the carbon byproducts, including carbon dioxide, may remain sequestered within the reservoir[21]. The produced gas stream contains a high proportion of hydrogen along with impurities such as carbon monoxide, carbon dioxide, and light hydrocarbons, which must be separated from the hydrogen stream prior to use.. While these methods are technologically feasible, they come with inherent challenges. The energy required to sustain subsurface reactions is significant, making operational efficiency a key constraint. The scalability of hydrogen farming is another open question, as reaction rates may vary depending on local, often uncertain, geological conditions. Moreover, extracting hydrogen from engineered subsurface reservoirs could introduce additional production technological complexities, with impurities coming with the hydrogen stream, all increasing the costs compared to extracting pre-existing hydrogen accumulations.

Although hydrogen farming represents a promising long-term alternative, it does not eliminate the need for exploration. A naturally occurring, commercially viable hydrogen field would be a game-changer[22], while engineered solutions remain an expensive fallback. For now, the priority remains clear: we must first determine if a large natural hydrogen reservoir exists before shifting focus to artificial production methods.

Final Remarks: A Critical Moment for Hydrogen Exploration

Natural hydrogen represents a potentially transformative energy source, but its viability depends on whether we can find the missing giant field. The next decade will be crucial: either we confirm the existence of economically significant hydrogen accumulations, or we shift toward alternative production methods such as hydrogen farming.

For now, the evidence remains incomplete. While natural hydrogen has been observed globally, no discovery has yet proven its commercial value. If a major field is found, it could disrupt the global energy landscape. If not, it will remain a scientific curiosity; valuable for understanding Earth's subsurface processes but lacking immediate economic potential.

To answer this question definitively, we must act. To demomstrate viability, large-scale exploration, deep drilling, and regulatory support are the only paths forward. The search for the big one is on.

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