The Search for Natural Hydrogen

A Hidden Energy Giant or an Elusive Dream?

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VIEWPOINT

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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 minimize 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.

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] (Figure 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 has not 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 nonreactive 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, permeable 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 As hydrogen is an indirect greenhouse gas, hydrogen leakage to the atmosphere will offset the climate benefits of displacing fossil fuel emissions (see Hauglustaine et al.[13] for a range of examples). 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 minimize 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.

WHERE TO LOOK: GEOLOGICAL TRAPS FOR HYDROGEN ACCUMULATION

If a major hydrogen field exists, it is most likely hidden in a geological trap[14] that has prevented its escape over geologic time. Similar to hydrocarbons, hydrogen requires sealed

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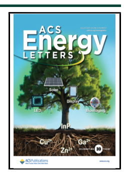

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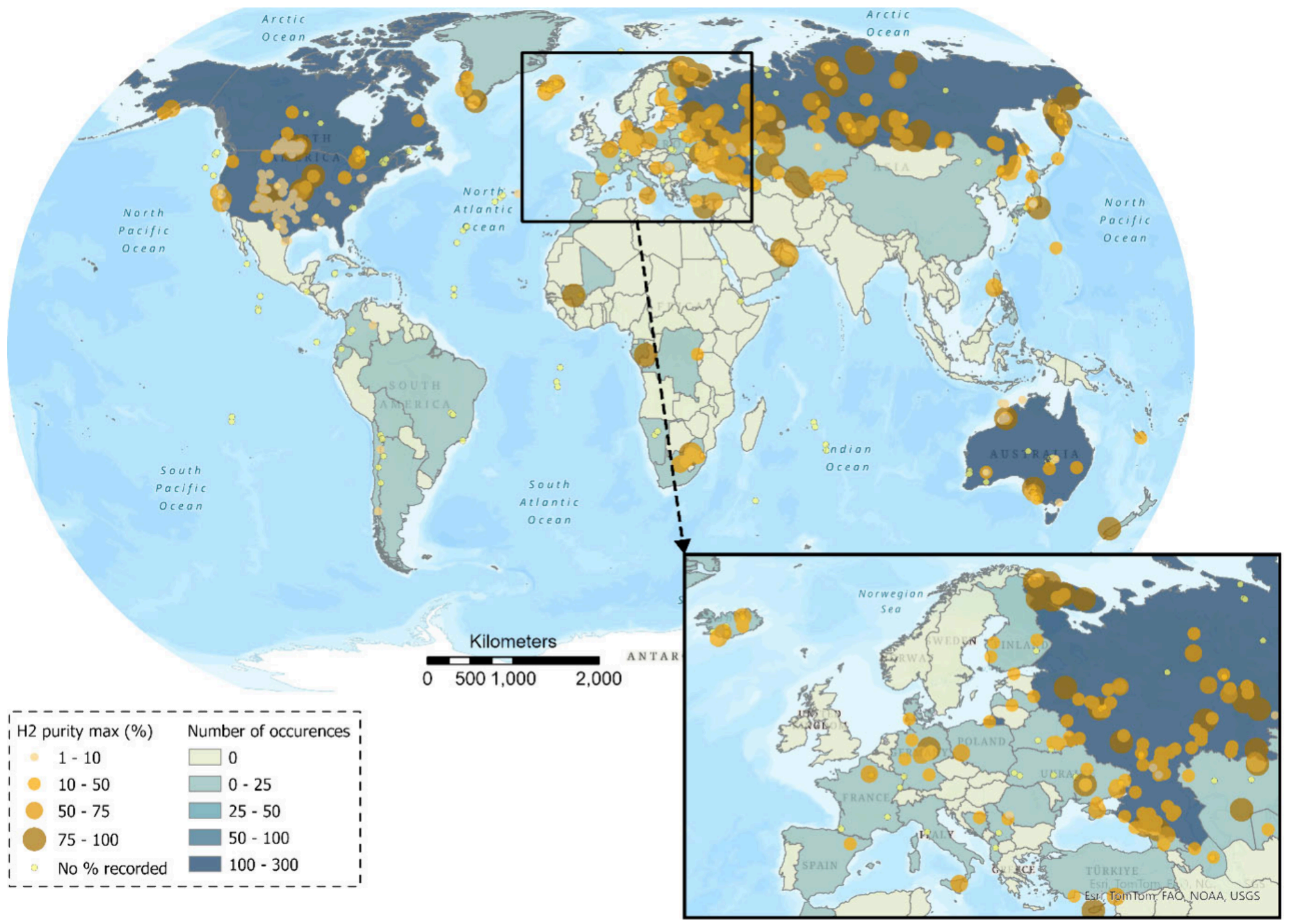

Figure 1. Global distribution of natural hydrogen occurrences. Documented hydrogen seepages and subsurface accumulations across diverse geological settings indicate widespread generation processes. The map highlights reported maximum hydrogen purity levels, with higher concentrations suggesting potential 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. The compiled dataset is available; see Supporting Information for access details.

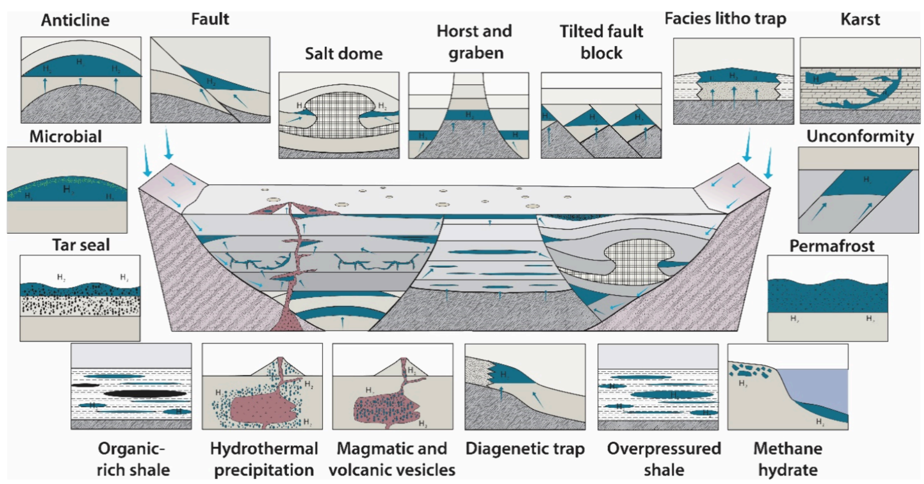

Figure 2. Potential geological traps for natural hydrogen accumulations. Hydrogen can accumulate in a variety of subsurface environments if effective sealing mechanisms prevent its escape. Structural traps, such as anticlines, faults, salt domes, horst and graben systems, and tilted fault blocks, may 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.

reservoirs to remain concentrated. Various structures may play a role in hydrogen accumulation, from anticlines and fault bounded reservoirs to salt domes[15] and sedimentary formations with permeability contrasts.[16] Figure 2 provides a conceptual framework for different trap types that could be relevant for hydrogen retention. Some hydrogen may even be retained under permafrost, cold-trapping, or low-temperature subsurface conditions, or be 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).

Some researchers argue that hydrogen fields may require specific conditions to remain stable.[17] 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 time scales. To date, the lack of dedicated deep hydrogen exploration wells[18] 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 toward a faster issuing of drilling licenses, a larger capital spending and an elucidation of the geological and biogeochemical conditions that grant maximum hydrogen accumulation (Figure 3).

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 financial 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[19] 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.

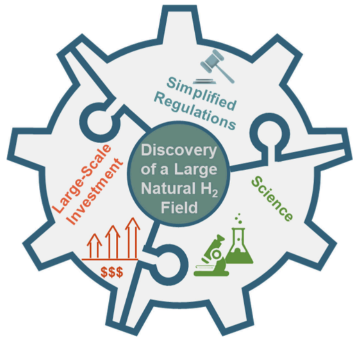

Figure 3. Key elements required for the discovery of a large natural hydrogen field. The successful identification of an economically viable hydrogen reservoir depends on the interplay between scientific research, regulatory frameworks, and financial investment. Advancing geological and geochemical understanding 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.

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. Importantly, even large accumulations may not be viable unless the rate of hydrogen generation and migration is sufficient to sustain production. Reservoir characteristics can vary significantly, especially in ultramafic rocks, where the production rate depends on the presence and connectivity of natural fractures. Serpentinization is an exothermic process that can locally increase temperature, enhance fracturing, and improve porosity, which may in turn increase hydrogen release. However, careful operation is essential, as serpentinization leads to solid-volume expansion that can raise pore pressure and potentially trigger seismic activity if not properly managed. The difference between an isolated hydrogen pocket and a sustainable resource lies in whether the gas can remain trapped at useful concentrations and can be extracted at a practical and safe rate. Without bold investment and exploration efforts, hydrogen's economic potential will remain theoretical.

IF THE BIG ONE DOES NOT 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[20] 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.[21] 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.[22] The produced gas stream contains a high proportion of hydrogen along with impurities such as carbon monoxide, carbon dioxide, and light hydrocarbons,

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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,[23] 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. The only known example of natural hydrogen extraction is in Bourakébougou, Mali, where a small-scale field has supplied local power needs, but the reservoir is limited in size and does not yet demonstrate sustained, scalable production. 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 demonstrate 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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■ ASSOCIATED CONTENT

Supporting Information

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Comprehensive classification of natural hydrogen traps in the subsurface (Table S1). This table categorizes all known geological mechanisms that control hydrogen accumulation and retention. Structural traps (e.g., anticlines, fault-bounded reservoirs, salt domes) form due to deformation, creating enclosed spaces where hydrogen can accumulate. Geographic data set and full description of mapped hydrogen occurrences used in , including raw GIS data for each observation (PDF)

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Notes

Views expressed in this Viewpoint are those of the authors and not necessarily the views of the ACS.
The authors declare no competing financial interest.

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■ REFERENCES

(1) Zgonnik, V. The Occurrence and Geoscience of Natural Hydrogen: A Comprehensive Review. *Earth-Science Rev.* **2020**, *203*, 103140.

(2) Odenweller, A.; Ueckerdt, F.; Nemet, G. F.; Jensterle, M.; Luderer, G. Probabilistic Feasibility Space of Scaling up Green Hydrogen Supply. *Nat. Energy* **2022**, *7* (9), 854–865.

(3) Stalker, L.; Talukder, A.; Strand, J.; Josh, M.; Faiz, M. Gold (Hydrogen) Rush: Risks and Uncertainties in Exploring for Naturally Occurring Hydrogen. *APPEA J.* **2022**, *62* (1), 361–380.

(4) Yedinak, E. M. The Curious Case of Geologic Hydrogen: Assessing Its Potential as a Near-Term Clean Energy Source. *Joule* **2022**, *6* (3), 503–508.

(5) Hassanpouryouzband, A.; Wilkinson, M.; Haszeldine, R. S. Hydrogen Energy Futures–Foraging or Farming? *Chem. Soc. Rev.* **2024**, *53* (5), 2258–2263.

(6) Osselin, F.; Soulaine, C.; Fauguerolles, C.; Gaucher, E. C.; Scaillet, B.; Pichavant, M. Orange Hydrogen Is the New Green. *Nat. Geosci.* **2022**, *15* (10), 765–769.

(7) Prinzhofer, A.; Tahara Cissé, C. S.; Diallo, A. B. Discovery of a Large Accumulation of Natural Hydrogen in Bourakebougou (Mali). *Int. J. Hydrogen Energy* **2018**, *43* (42), 19315–19326.

(8) Frery, E.; Langhi, L.; Maison, M.; Moretti, I. Natural Hydrogen Seeps Identified in the North Perth Basin, Western Australia. *Int. J. Hydrogen Energy* **2021**, *46* (61), 31158–31173.

(9) Zgonnik, V.; Beaumont, V.; Deville, E.; Larin, N.; Pillot, D.; Farrell, K. M. Evidence for Natural Molecular Hydrogen Seepage Associated with Carolina Bays (Surficial, Ovoid Depressions on the Atlantic Coastal Plain, Province of the USA). *Prog. Earth Planet. Sci.* **2015**, *2*, 1–15.

(10) Lefeuvre, N.; Thomas, E.; Truche, L.; Donzé, F.; Cros, T.; Dupuy, J.; Pinzon-Rincon, L.; Rigollet, C. Characterizing Natural Hydrogen Occurrences in the Paris Basin from Historical Drilling Records. *Geochemistry, Geophys. Geosystems* **2024**, *25* (5), No. e2024GC011501.

(11) Hassanpouryouzband, A.; Joonaki, E.; Edlmann, K.; Haszeldine, R. S. Offshore Geological Storage of Hydrogen: Is This Our Best Option to Achieve Net-Zero? *ACS Energy Lett.* **2021**, *6* (6), 2181–2186.

(12) Gregory, S. P.; Barnett, M. J.; Field, L. P.; Milodowski, A. E. Subsurface Microbial Hydrogen Cycling: Natural Occurrence and Implications for Industry. *Microorganisms* **2019**, *7* (2), 53.
(13) Hauglustaine, D.; Paulot, F.; Collins, W.; Derwent, R.; Sand, M.; Boucher, O. Climate Benefit of a Future Hydrogen Economy. *Commun. Earth Environ.* **2022**, *3* (1), 295.
(14) Mitra, S. Fault-Propagation Folds: Geometry, Kinematic Evolution, and Hydrocarbon Traps. *Am. Assoc. Pet. Geol. Bull.* **1990**, *74* (6), 921−945.
(15) Posey, H. H.; Kyle, J. R. Fluid-Rock Interactions in the Salt Dome Environment: An Introduction and Review. *Chem. Geol.* **1988**, *74* (1−2), 1−24.
(16) Hurst, A.; Rosvoll, K. J. Permeability Variations in Sandstones and Their Relationship To Sedimentary Structures. *Reservoir Characterization II*; Academic Press: San Diego, CA, 1991; pp 166−196. DOI: 10.1016/b978-0-12-434066-4.50011-4.
(17) Thaysen, E. M.; McMahon, S.; Strobel, G. J.; Butler, I. B.; Ngwenya, B. T.; Heinemann, N.; Wilkinson, M.; Hassanpouryouzband, A.; McDermott, C. I.; Edlmann, K. Estimating Microbial Growth and Hydrogen Consumption in Hydrogen Storage in Porous Media. *Renew. Sustain. Energy Rev.* **2021**, *151*, 111481.
(18) Sun, B.; Zhang, M.; Sun, Q.; Zhong, J.; Shao, G. Review on Natural Hydrogen Wells Safety. *Nat. Commun.* **2025**, *16* (1), 369.
(19) Wang, L.; Jin, Z.; Chen, X.; Su, Y.; Huang, X. The Origin and Occurrence of Natural Hydrogen. *Energies* **2023**, *16* (5), 2400.
(20) Etiope, G. Natural Hydrogen Extracted from Ophiolitic Rocks: A First Dataset. *Int. J. Hydrogen Energy* **2024**, *78*, 368−372.
(21) Hassanpouryouzband, A.; Veshareh, M. J.; Wilkinson, M.; Nick, H. M.; Ngwenya, B. T.; Haszeldine, R. S. In Situ Hydrogen Generation from Underground Fossil Hydrocarbons. *Joule* **2025**, *9* (2), 101809.
(22) Salahshoor, S.; Afzal, S. Subsurface Technologies for Hydrogen Production from Fossil Fuel Resources: A Review and Techno-Economic Analysis. *Int. J. Hydrogen Energy* **2022**, *09*, 2023.
(23) Ellis, G. S.; Gelman, S. E. Model Predictions of Global Geologic Hydrogen Resources. *Sci. Adv.* **2024**, *10* (50), No. eado0955.