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Stimulated Geologic Hydrogen Production: State of Play, Challenges, and Key Questions to Ask

Abstract

Stimulated geologic hydrogen production is increasingly viewed as a compelling alternative to conventional low-carbon hydrogen methods, which struggle with cost, scalability, and intermittency. Unlike conventional natural hydrogen extraction, which depends on rare and unpredictable subsurface accumulations, stimulated production actively engineers geological conditions to generate hydrogen in situ using techniques such as Electrical Reservoir Stimulation, Advanced Weathering Enhancement, among others. While these approaches – currently at Technology Readiness Levels 2-6 – promise low-cost, low-emission hydrogen, key uncertainties remain. Currently, critical challenges include selecting optimal sites, ensuring sustained production, managing environmental and geo-mechanical risks, developing robust monitoring, and integrating hydrogen into existing value chains. Thus, large-scale pilots and interdisciplinary research are essential to determine whether stimulated geologic hydrogen can emerge as a scalable and commercially viable pillar of the future energy system.

Introduction

Since the 2010s, with the commercial exploitation of the first natural hydrogen (H_2) field in Bourakébougou, Mali – accidentally discovered almost a quarter of a century earlier – the global interest in natural (or 'white') hydrogen, i.e. H_2 generated in the subsurface through geological processes, has only been increasing (Prinzhoffer and Deville, 2015, Prinzhofer et al, 2019, Zgonnik, 2020 and Bendall, 2022). This form of hydrogen is gaining attention as a promising alternative to conventional low-carbon H_2 production methods due to its potential to overcome two of their most important limitations: cost and scalability. Indeed, despite its strategic importance in decarbonisation pathways, green hydrogen – produced via electrolysis using renewable power – remains prohibitively expensive (*Table 1*) and difficult to scale because of electrolyser technology limitations and relatively slow ramp-up of renewables[1]. Furthermore, its dependence on intermittent renewable energy sources also implies variable hydrogen output, which complicates integration with industrial processes that demand a consistent supply (Patonia et al, 2023). Moreover, the infrastructure that could smooth its consumption pattern, including large-scale storage, remains underdeveloped in most countries (Patonia et al, 2025).

[1] In Europe, for instance, the development of renewable energy sources for green hydrogen production is hampered by the additionality principle, which requires that the electricity used for electrolysis must come from newly built renewable capacity rather than existing sources, thereby limiting supply and increasing costs (European Union, 2023).

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Table 1: Key hydrogen generation processes, their estimated carbon intensity, and levelised cost of production

Origin	Feedstock	Production technology/ mechanism	CO_2 abatement/ elimination technology	Estimated carbon intensity ($kg\text{-}CO_{2e}/kg\text{-}H_2$)	Estimated levelised cost of production (USD/kg)
Manufactured	Natural gas	Steam methane reforming	No	10.09-17.21	1.03-2.16
			CCS	2.97-9.16	1.22-2.26
	Coal	Coal gasification	No	14.4-30.9	0.96-1.88
			CCS	0.78-10.35	1.40-3.60
	Wind energy and water	Electrolysis of water	N/a	0.52-2.2	3.56-10.82
	Solar energy and water			1.32-7.1	3.34-14.87
Naturally occurring	Olivine and water	Hydrothermal alteration (incl. serpentinisation)	N/a	0.4-1.5	Potentially <1
	Hydrocarbons/ biomass and heat	Deep-seated/ thermal decomposition (incl. volcanic degassing)			
	Water and ionising radiation	Radiolysis			

Source*:* Adapted from Patonia et al (2024).

Blue hydrogen, in turn, which is produced from fossil fuels with carbon capture and storage (CCS), is often presented as a transitional solution (Dickel, 2020). However, it remains roughly at least twice as expensive as grey hydrogen (*Table 1*), and its lifecycle emissions are subject to significant uncertainty due to factors such as methane leakage and incomplete CO_2 capture – typically averaging around 60 percent, with best-case scenarios reaching 90 percent (IEEFA, 2023). In addition, the need for creating extensive CO_2 transport and storage infrastructure further limits its deployment both from the techno-economic and socio-political perspectives in few places such as the US and the Middle East.

In this context, natural geologic hydrogen is increasingly seen as a potentially superior alternative to green and blue hydrogen, primarily due to its exceptionally low expected carbon intensity and production costs (*Table 1*). This perception is reinforced by the example of Hydroma – currently the only company producing native H_2 – which claims that hydrogen from its Malian project can be delivered at a cost below USD 1 per kilogram with near-zero emissions (Hydroma, 2023)[2]. Drawing on Hydroma's experience, many entities exploring geologic hydrogen suggest they could achieve similar, if not better, outcomes. However, despite several years of exploration activities and a series of promising announcements from countries ranging from Australia to the United States, and from Brazil to France and Albania, all discoveries outside Mali remain at the prospecting or early testing stages. To date, no other commercial-scale reserves have been confirmed (Patonia et al., 2024).

In this context, new initiatives are emerging focused on the stimulated production of geologic hydrogen. In particular, rather than searching for exact deposits of native H_2 in naturally favourable subsurface conditions – which have so far proven to be apparently rare and uncertain – this approach aims to artificially recreate such conditions using specific engineering techniques. By mimicking and

[2] The Bourakebougou-1 well in Mali produces 1,500 m^3 of hydrogen per day from a shallow reservoir at 110 m depth, equivalent to 2.9 BOE/d (Everts, Bonnie, and Loosveld, 2024 and Patonia et al, 2024). At this rate, thousands of wells would be required to match a small gas field, or roughly ten wells to equal the output of a typical onshore wind turbine (ibid).

accelerating the key geochemical reactions responsible for hydrogen generation, companies and research initiatives involved in stimulated geologic hydrogen production may significantly reduce or even eliminate the need for costly exploration with unknown results, while still producing a final product with higher success rate and similar characteristics – low-carbon native hydrogen at low production cost. However, as most of these initiatives are still in their infancy, considerable uncertainties remain.

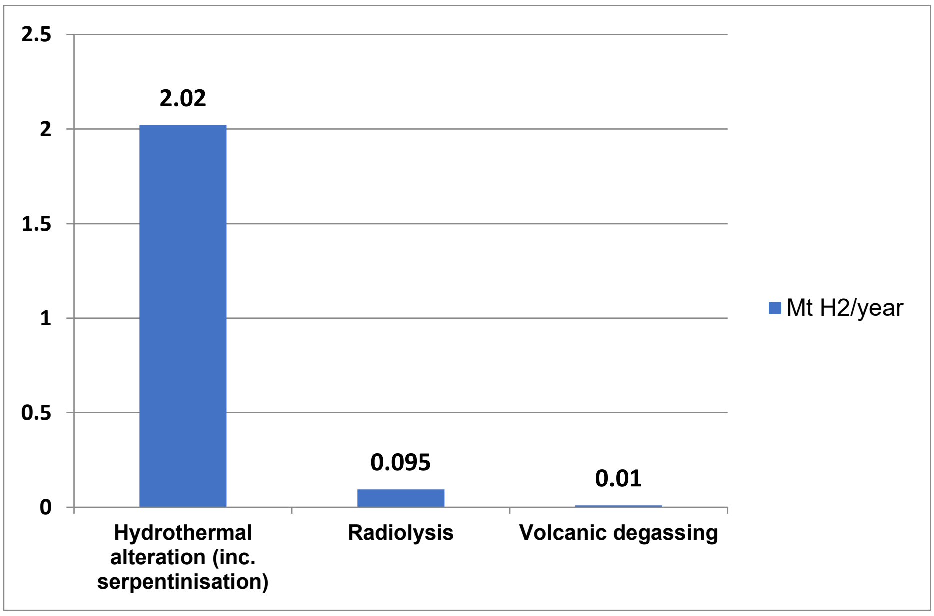
This Energy Insight therefore explores the technical foundations, current research landscape, and potential applications of stimulated geologic hydrogen production. It focuses on answering the following key questions:

- Why might we need stimulated geologic hydrogen production?
- What are the key current technologies, techniques, and methods under consideration?
- What are their prospects and limitations?
- What other fundamental questions need to be answered before these technologies could ramp up to commercial production of stimulated geologic hydrogen?

1. Why might we need stimulated geologic hydrogen production?

The discovery of natural hydrogen accumulation in Bourakébougou, along with numerous seeps and vents worldwide, has catalysed a global wave of interest in geological hydrogen – that is, hydrogen generated abiotically (i.e. by non-living factors or mechanisms) through natural subsurface processes such as serpentinisation, radiolysis, and iron oxidation (Prinzhofer and Deville, 2015 and Zgonnik, 2020). In principle, hydrothermal alteration (including serpentinisation), radiolysis, and volcanic degassing are currently regarded as the main geologic sources of abiotic H_2 (*Figure 1*). These processes can be summarised schematically: radiolysis produces H_2 when water molecules are dissociated by radioactive decay (via alpha, beta, or gamma radiation); volcanic degassing releases hydrogen when SO_2 escapes at low pressure; and hydrous alteration of rocks produces H_2 when water is reduced during the oxidation of ferrous to ferric iron (Klein, Tarnas, and Bach, 2020).

Figure 1: Estimated annual generation of abiotic hydrogen by main geologic sources



Source: Adapted from Klein, Tarnas, and Bach (2020).

The interest towards exploring and exploiting native hydrogen is not surprising, since the theoretical potential is vast: reputable institutions like the US Geological Survey claimed that, even if only a small fraction of Earth's naturally generated H_2 were technically and economically recoverable, it could be sufficient to meet projected global hydrogen demand – estimated at up to 500 million tonnes per year – for centuries (Ellis and Gelman, 2024, Hydrogen Central, 2024, and Pwc, 2025). This promise has spurred exploration efforts in the United States, Australia, France, Canada, and elsewhere, with growing government support and private-sector involvement (Patonia et al, 2024).

Yet, despite substantial investment and enthusiasm, efforts to identify commercially viable accumulations have so far proved inconclusive. In fact, most known occurrences of native hydrogen have been discovered serendipitously – in most cases during mineral or hydrocarbon exploration – rather than as the result of systematic prospecting (Zgonnik, 2020). In addition, the bulk of identified hydrogen emissions turned out to be surface seeps or relatively shallow subsurface flows – i.e. not large-scale accumulations suitable for commercial development (Patonia et al, 2024). While on-going exploration may yield new finds, several key limitations constrain the scalability of this pathway.

In this respect, one of the crucial concerns is the accessibility of natural hydrogen deposits. In fact, many of the most promising geological formations for hydrogen generation are located offshore, at significant depths, or in geologically complex regions that are difficult and expensive to explore and develop (Ellis and Gelman, 2024). Therefore, even where hydrogen occurs as free gas – the only form currently viable for industrial production using existing oil and gas technologies – it is often too deeply buried, too remote from end-use markets, or found in concentrations too low to support commercial extraction (Blay-Roger et al, 2024 and Everts, Bonnie, and Loosveld, 2025).

More fundamentally, several geological uncertainties continue to hamper the search for viable hydrogen reservoirs. Although the processes that generate native hydrogen are well established in theory, their real-world rates, spatial continuity, and environmental dependencies are still relatively poorly understood (Prinzhofer and Deville, 2015 and Patonia et al, 2024). In addition, the mechanisms of hydrogen accumulation, a key prerequisite for economically viable extraction with the help of oil and gas technologies, remain particularly under-researched (Blay-Roger et al, 2024 and Everts, Bonnie, and Loosveld, 2025). Therefore, without a clearer understanding of how hydrogen becomes trapped and concentrated in subsurface formations, it is difficult to predict where extractable volumes might occur. This knowledge gap also limits the effectiveness of surface and subsurface exploration tools, which remain in their infancy compared to those used in the oil and gas sector (Zgonnik, 2020).

As a result, geologists and energy researchers are calling for progress in at least three key areas that are essential for the successful exploration of geologic hydrogen:

(1) a fundamental understanding of hydrogen generation and migration systems,

(2) advanced surface geophysical and geochemical detection methods, and

(3) more sophisticated tools for subsurface imaging and modelling.

Until such advances are achieved, large-scale exploration of native hydrogen will remain scientifically uncertain and financially risky – an endeavour that is high in potential impact but low in probability (Patonia et al, 2024).

In light of these constraints and uncertainties, growing attention is being directed towards an alternative strategy: stimulated geological hydrogen production. Instead of relying on rare geological conditions that result in viable accumulations of natural hydrogen, this emerging approach aims to engineer favourable subsurface environments to actively generate hydrogen from reactive rock formations (Templeton et al, 2024). This is achieved through stimulation techniques – such as thermal, electrical, chemical, or mechanical methods – that enhance natural hydrogen-producing reactions in situ, under geological conditions (ibid and Awosiji, Graham, and Mukerji, 2025).

Here, the key objective is to produce hydrogen directly at the source, minimising the need for its migration or accumulation in large reservoirs. Because of its attractiveness, this concept is currently gaining momentum among researchers and policymakers. For instance, the US Department of Energy, has identified the development of subsurface stimulation technologies as a critical pathway for unlocking geological hydrogen as a scalable, low-emission energy resource (DOE, 2023). Similar initiatives are now under way in Europe and Canada, where both public agencies and private firms are beginning to investigate the feasibility of engineered hydrogen production from ophiolitic and ultramafic rock formations[3].

In this context, stimulated geological hydrogen production represents not only a complement to traditional exploration-based strategies, but a potentially more predictable and controllable means of accessing Earth's vast subsurface hydrogen resources.

2. What are the key technologies and methods currently under consideration?

As described, the inherent uncertainties and limitations associated with the exploration and extraction of native hydrogen have driven increasing interest in alternative approaches to exploiting and harnessing this potentially vast energy resource. At the moment, stimulated geologic hydrogen production represents the most substantial alternative to conventional production methods using existing oil and gas technologies. At the same time, given that the key natural processes responsible for the formation of native hydrogen are yet to be fully identified and understood, various stimulation techniques and methods are currently being used to primarily mimic the natural mechanisms behind native H_2 origination – primarily hydrothermal alteration in a form of serpentinisation – and it is likely that new stimulated geologic hydrogen production mechanisms will emerge in the future. Nevertheless, at present, most efforts understandably focus on facilitating and accelerating reactions that are either similar or identical to well-established processes known to be associated with geologic H_2 synthesis in the natural environment.

Table 2 presents the key technologies for stimulated geological hydrogen production technologies.

- **Electrical Reservoir Stimulation (ERS)**

Electrical Reservoir Stimulation (ERS) is a subsurface engineering technique that injects high-voltage electric currents into iron-rich rock formations to generate localized heating and controlled fracturing (Eden GeoPower, 2024). This process generally aims to activate geochemical reactions – such as serpentinisation and silicate weathering in ultramafic and mafic rocks[4] – that release molecular hydrogen, enhance reservoir permeability, and facilitate the mineralisation of CO_2 into stable carbonates and dissolved bicarbonates, contributing to geological carbon sequestration (ibid and Unified Patents, 2018). Drawing on principles from geothermal energy extraction and unconventional hydrocarbon stimulation, ERS provides precise control over fracture propagation without the need for fluid injection, thereby lowering water consumption and reducing environmental impact (*Table 2*).

In practice, ERS applies pulsed or low-frequency electrical currents between wells or within a reservoir to heat the rock matrix and induce micro-fractures through thermal expansion and vibrational forces (Egert, Neupane, and Jin, 2025). This heating also reduces fluid viscosity and clears blockages in sediment pores without chemical additives or proppants typically used in hydraulic fracturing (Business Wire, 2022). The absence of large-volume water use, the reduced risk of induced seismicity, and the ability to direct fractures precisely make ERS particularly suitable for environmentally sensitive regions and areas facing water scarcity (ibid).

On the other hand, ERS is constrained by geological suitability, as it requires formations with high electrical conductivity, most commonly ultramafic and other iron-rich lithologies (Agrawal, 2024 and Egert, Neupane, and Jin, 2025). Although it is the most advanced of the stimulated geologic hydrogen manufacturing approaches in terms of field testing that is also projected to be highly productive with thousands of tonnes of clean hydrogen being generated on an annual basis, its Technology

[3] Ophiolitic formations are slices of oceanic crust and mantle emplaced on land, often exposing ultramafic rocks – silica-poor, magnesium- and iron-rich mantle rocks that can generate hydrogen through serpentinisation (Coleman, 1977).

[4] Serpentinisation involves the hydration of olivine and pyroxene-rich ultramafic rocks, converting CO_2 into stable carbonate minerals such as magnesite, while enhanced silicate weathering of mafic rocks (e.g., basalt) leads to bicarbonate formation that can be transported to oceans (Patonia et al, 2024). Electrical stimulation accelerates these reactions by increasing temperature and enhancing mineral surface reactivity (Kelemen and Matter, 2008).

Readiness Level (TRL) is still currently estimated at 5-6, which indicates successful pilot demonstrations but limited commercial deployment (ibid and Business Wire, 2022). Therefore, to be able to provide evidence of the promising nature of this method of stimulated geologic hydrogen production, developers such as Eden GeoPower, in partnership with ZeroGeo Energy, are actively conducting pilot projects in diverse locations, including the Samail Ophiolite in Oman, sites in the United States, and parts of Europe (Eden GeoPower, 2024). Although industrial scale production is still yet to be reached, these efforts managed to get support from large government initiatives such as the ARPA-E of the US[5] in order to scale ERS deployment while improving the environmental and economic performance of subsurface hydrogen production (ARPA-E, 2024).

- **Advanced Weathering Enhancement (AWE)**

Advanced Weathering Enhancement (AWE), in turn, focuses on accelerating natural serpentinisation processes through the engineered injection of water into ultramafic rock formations, such as peridotites and dunites, which are rich in olivine and pyroxene (GeoRedox, 2025). By increasing the rate and extent of water-rock interactions, this method promotes the oxidation of ferrous minerals (Fe^{2+}) into ferric minerals (Fe^{3+}), producing molecular H_2 as a by-product alongside stable mineral phases such as serpentine and magnetite (ibid). Companies like GeoRedox Corporation and Sage Geosystems are currently pursuing field demonstrations of AWE in the United States, aiming to validate its technical feasibility, optimise injection strategies, and evaluate the long-term stability of the reaction zones in the foreseeable future (GeoRedox, 2024 and Energy News, 2025). The approach is inherently catalyst-free and offers potential cost-efficiency by utilising naturally occurring geological processes without expensive chemical inputs (ibid).

However, AWE faces important challenges before it can be deployed at scale. These primarily include the monitoring of subsurface geochemical changes to prevent unintended impacts on groundwater, ensuring environmental safety, managing subsurface pressure and flow pathways, and addressing scalability limitations linked to the distribution and accessibility of suitable ultramafic formations (ibid). Therefore and because of the relative infancy of all major pilot projects, at present, the exact expected output is hard to predict, as AWE technologies are generally assessed at TRL 4-5 – i.e. similar to and slightly lower than that of ERS (ibid). This is generally reflecting their progress beyond laboratory studies but still highlights the need for a pilot-scale validation under operational conditions.

- **Fracture stimulation (hydraulic/mechanical)**

Fracture stimulation (hydraulic/mechanical) in the geologic hydrogen context involves deliberately creating or reactivating fractures in subsurface reactive rock formations to increase permeability and expose fresh mineral surfaces, thereby accelerating hydrogen-generating reactions such as serpentinisation (Egert, Neupane, and Jin, 2025). It is distinct from ERS, which uses electric currents to enhance fluid flow or stimulate electrochemical reactions within a reservoir, and from AWE, which accelerates mineral weathering rates through optimised chemical, thermal, or biological treatments. Unlike ERS and AWE, fracture stimulation is a purely geo-mechanical intervention that relies on creating physical pathways in the rock mass, typically at depth (ibid).

At the moment, the most notable hydrogen-specific fracture stimulation projects include New England Research's Accelerated Mechanical Promotion (AMP) of serpentinisation, funded by the US DOE and ARPA-E, which uses controlled fracturing to expose ultramafic rocks, and OptiRock Group's optimisation of fracture networks to increase exposure of iron-rich lithologies (NER, 2022, OptiRock Group, 2022, and SBIR, 2022). Although there is definitely scope to grow and expand, both currently remain at low technology readiness levels (2-4) and are subject to stringent seismic and environmental monitoring (ibid and Boyet et al, 2024). In principle, while the method borrows from oil, gas, and enhanced geothermal stimulation, its application to hydrogen is at an early stage, with significant risks including induced seismicity, fault reactivation, and permeability loss from mineral precipitation (ibid).

[5] ARPA-E stands for the Advanced Research Projects Agency – Energy and represents a United States government agency under the US Department of Energy (DOE) that funds transformational energy research and development (ARPA-E, 2025).

Table 2: Key stimulated geologic hydrogen production technologies

Technology type	Stimulation method	Main mechanism	Natural processes mimicked	Key pros	Key cons	TRL level	Key institutions / companies	Key locations
Electrical Reservoir Stimulation (ERS)	Injection of electricity to heat and fracture iron-rich rock	Thermal + mechanical stimulation	• Hydrothermal alteration (serpentinisation) • Enhanced silicate weathering • Mineral carbonation	• Precise fracture control • Low water use	• Requires conductive formations	5-6	*Eden GeoPower (with ZeroGeo Energy)*	USA, Oman, Europe
Advanced Weathering Enhancement (AWE)	Water injection + engineered weathering to promote serpentinisation	Water-rock chemical enhancement	• Hydrothermal alteration (serpentinisation) • Silicate weathering	• Catalyst-free • Low-cost	• Environmental monitoring & scalability challenges	4-5	*GeoRedox Corporation, Sage Geosystems*	USA
Fracture stimulation (hydraulic/ mechanical)	Hydraulic or mechanical fracturing to increase permeability	Fracture propagation + increased surface	• Hydrothermal alteration (serpentinisation) • Enhanced hydrogen degassing from fractured ultramafic rocks (tectonic degassing)	• Builds on oil & gas practice	• Risk of induced seismicity; regulatory constraints	2-4	*OptiRock, New England Research; ARPA-E labs*	USA
Chemical stimulation (acid injection)	Injection of acids or oxidants to dissolve ferrous minerals	Chemical oxidation of iron-bearing minerals	• Serpentinisation (accelerated oxidation of Fe (II) silicates)	• Fast action • Scalability possible	• Hazards and groundwater risk	2-3	*Lawrence Livermore NL, Texas Tech University*	USA
Biological stimulation (microbial)	Activation of hydrogen-producing microbes in subsurface	Biological water-rock interactions	• Biogenic hydrogen from microbial iron reduction and water-rock microbe interactions	• Low energy • Sustainable	• Slow rates and ecological control challenges	2	*Biogeochemical research groups*	USA, Canada, Europe
Geothermal heating (closed-loop EGS)	Stimulating impermeable hot dry rock for heat reservoirs	Heat-driven geochemical stimulation	• Thermally-enhanced silicate dissolution and associated hydrogen production	• Dual-energy value	• High upfront drilling costs	3-4	*Geothermal R&D (France, Germany, Australia)*	France, Germany, Australia
Pressure reduction (depressurisation)	Controlled depressurisation of H_2-bearing formations	Pressure-driven degassing	• Tectonic degassing and hydrogen release from pressure drop in faulted ultramafic formations	• Simple concept	• Limited by geology and natural H_2 presence	2	*University research projects*	Emerging sites

Source: Adapted from Netskina et al (2018), Vallier et al (2019), Zgonnik (2020), Business Wire (2022), NER (2022), OptiRock Group (2022), SBIR (2022), Australian Government (2023), Lototskyy et al (2023), ARPA-E (2024), Boyet et al (2024), Eden GeoPower (2024), GFZ (2024), Hamlehdar, Beardsmore, and Narsilio (2024), Iwanenko et al (2024), LLNL (2024), Texas Tech University (2024), Dawaidar (2025), Egert, Neupane, and Jin (2025), Energy News (2025), GeoRedox (2025), Patonia et al (2025), Peng et al (2025).

- **Chemical stimulation (acid injection)**

Chemical stimulation (conducted primarily via acid injection) is aimed to accelerate hydrogen generation by dissolving iron-bearing minerals in subsurface formations, which enhances geochemical reactions like serpentinisation (LLNL, 2024 and Texas Tech University, 2024). This method is expected to enable rapid hydrogen production but carries risks such as groundwater contamination and equipment corrosion, requiring corrosion-resistant materials and environmental safeguards (ibid). Therefore, at the moment, research at the Lawrence Livermore National Laboratory (LLNL) and Texas Tech, supported by the US Department of Energy's ARPA-E program, focuses primarily on optimising acid injection techniques and catalytic stimulation, which is currently at TRL 2-3 (ibid). Alternative acid-based methods, such as acetic acid hydrolysis of magnesium hydride and hydrochloric acid decomposition of sodium borohydride, also demonstrate notable hydrogen yields (Netskina et al, 2018 and Lototskyy et al, 2023). At the same time, while promising, apart from maturing towards full commercialisation, acid stimulation techniques must address environmental and operational challenges to enable sustainable hydrogen production.

- **Biological stimulation**

In contrast to other methods, biological stimulation leverages native subsurface microbial communities capable of producing hydrogen through metabolic pathways such as fermentation and anaerobic respiration (Ivanenko et al, 2024). By injecting nutrients or adjusting environmental factors like pH and redox conditions, this approach enhances microbial hydrogen generation in situ, offering a sustainable and energetically efficient alternative to chemical approaches. However, unlike them, biological stimulation is limited by relatively slow hydrogen production rates and challenges related to managing complex subsurface microbial ecosystems (Dawaidar, 2025).

Current research in the field is led primarily by universities and research institutions, which conduct mostly laboratory and small-scale field experiments to optimise microbial stimulation techniques (ibid and Gregory et al, 2019). These efforts, partially funded by state entities like the US Department of Energy and Natural Resources Canada, place the technology at approximately TRL 2, which describes it as that at a very early development stage far from full-scale commercialisation in the foreseeable future (ibid). Therefore, any commercial applications remain nascent, although they nevertheless include start-ups like LanzaTech, which explore microbial bioconversion for sustainable fuels, highlighting the growing interest in microbial hydrogen technologies (LanzaTech, 2024).

- **Geothermal heating (closed-loop enhanced geothermal systems)**

Closed-loop enhanced geothermal systems (EGS) represent another avenue for sustainable hydrogen production by harnessing heat from deep, impermeable hot dry rock formations. Unlike traditional geothermal methods that rely on natural permeability, closed-loop EGS circulate fluids through engineered wells in a sealed system, extracting geothermal heat that can drive geochemical reactions producing hydrogen, while simultaneously enabling co-generation of geothermal energy (Hamlehdar, Beardsmore, and Narsilio, 2024). Active research initiatives are currently underway in countries such as France, Germany, and Australia, among others.

In particular, the French Geological Survey (BRGM) is advancing this technology at the Soultz-sous-Forêts site, focusing on integrating hydrogen generation within closed-loop geothermal stimulation (Vallier et al, 2019). Similarly, Germany’s Groß Schönebeck project, operated by the GFZ German Research Centre for Geosciences, investigates enhanced heat recovery and thermochemical hydrogen production (GFZ, 2024). Australia’s CSIRO and Geoscience Australia, in turn, lead efforts into superhot rock geothermal systems designed for electricity and hydrogen co-production, addressing key challenges of deep drilling and reservoir management (Australian Government, 2023). Nevertheless, despite its potential, just like most other stimulation techniques, closed-loop EGS is currently at a relatively early technology readiness level (TRL 3-4), hindered by high upfront drilling costs and technical challenges associated with maintaining efficient heat transfer and reservoir stability.

- **Pressure reduction (depressurisation)**

Finally, pressure reduction, or depressurisation, is a technique aimed at stimulating the release of hydrogen gas naturally trapped in subsurface geological formations by lowering the pressure within these reservoirs. This process leverages the principle that decreasing pressure reduces gas solubility in formation fluids, encouraging degassing of native hydrogen accumulations (Zgonnik, 2020). Compared to other hydrogen production methods, pressure reduction is expected to be relatively low-cost and conceptually simple, relying primarily on existing geological conditions. However, its feasibility is highly contingent upon the presence of economically significant hydrogen reserves, which, as mentioned, are far from being fully characterised globally (Peng et al, 2025). Consequently, pressure reduction technology is currently at an early stage of development, with a technology readiness level around 2, reflecting its status in conceptual research and small-scale laboratory investigations.

3. What are the key questions still unanswered?

The growing excitement around stimulated geologic hydrogen production should not be surprising. It promises an abundant, low-carbon energy source, freed from the rarity of naturally occurring hydrogen reservoirs and potentially capable of delivering cost-competitive volumes at scale. Yet, at the moment, the gap between laboratory success and a bankable industrial operation still remains very wide. Before these technologies can evolve into a dependable energy industry, a range of interconnected challenges must be addressed through coordinated field demonstrations, economic assessments, and regulatory alignment. Crucially, investors, regulators, and developers must move beyond asking 'Can it be done?' to confronting the deeper question: 'Can it be achieved reliably, safely, and profitably at scale?'

The following are the most critical areas where clarity is still lacking.

- **Which geological settings offer repeatable and predictable hydrogen yields under stimulation?**

The first and perhaps most fundamental issue is whether the industry can clearly define which geological settings consistently yield high, sustainable hydrogen production under stimulation. While ultramafic formations such as peridotites and serpentinites are widely considered prime candidates, their performance varies greatly depending on local mineralogy, temperature-pressure conditions, and fluid chemistry (McCollom, Klein, and Ramba, 2022). Other rock types, including certain basalts and shales with reactive iron-bearing minerals, may prove viable in some settings, but their reaction kinetics currently remain poorly documented. In these circumstances, developing a standardised geological 'playbook' – one that will allow developers to rapidly assess and rank potential sites – will be critical (ibid and Templeton et al, 2024). Without predictable site selection criteria, project timelines will be uncertain, and investor confidence will remain fragile.

- **What is the real, field-proven cost per kilogram when all lifecycle inputs are included?**

Even if the right formations are identified, there is the pressing question of cost. Headlines citing production costs below USD 1 per kilogram are enticing, but these figures often rest on idealised assumptions with little or no factual proof provided. Therefore, the real number can only be known once multi-year field data captures true energy input requirements, decline rates, and operational complexity. In this context, energy efficiency is central since stimulation techniques like ERS and AWE require significant energy to initiate and sustain reactions, and any erosion of net energy yield is extremely likely to quickly undermine competitiveness with green hydrogen from electrolysers (Mathur et al, 2024). In addition, the overall economic picture must factor in the full lifecycle: exploration, drilling, stimulation, monitoring, purification, transport, and eventual decommissioning – plus contingencies for equipment designed to resist hydrogen embrittlement and aggressive geochemical environments, etc. (Patonia et al, 2024). Closely related is the question of carbon intensity: how "low-carbon" is stimulated hydrogen in practice, once the energy inputs are fully accounted for, and where that energy comes from? Without transparent energy balances comparing input versus output, the climate credentials of the pathway remain uncertain.

- **Can production rates be maintained over commercially relevant timescales?**

Closely linked to cost is the challenge of sustaining production over time. Just like with most other emerging technology, laboratory and short-term pilot tests are great for scientific and exploratory purposes but they are, unfortunately, insufficient to predict whether stimulated reservoirs will maintain economically viable output for years or decades. In fact, reaction zones may lose activity due to mineral passivation, permeability decline, or fracture closure, among other factors (McCollom, Klein, and Ramba, 2022). In these circumstances, understanding decline curves – and developing low-cost, environmentally safe methods for re-stimulating reservoirs – is vital if developers hope to sign long-term supply agreements or finance infrastructure on the back of production forecasts.

- **How can environmental and geomechanical risks be quantified and mitigated to secure a social licence to operate?**

The environmental and geo-mechanical dimensions are equally critical to the business case. Accelerating subsurface reactions will inevitably alter geological and hydrological systems, raising the possibility of induced seismicity, aquifer contamination by mobilised heavy metals, or unexpected subsidence. These risks extend beyond technical challenges; they encompass permitting and social license concerns that can significantly delay or even terminate projects (Patonia et al, 2024). That is why the sector will need robust predictive models that integrate thermal, hydrological, mechanical, and chemical processes, paired with real-world monitoring data, to reassure regulators and local communities.

- **What reliable, real-time monitoring methods can be deployed in harsh subsurface conditions?**

Monitoring itself represents another major gap. Stimulated hydrogen production demands real-time surveillance of chemical, thermal, and structural changes deep underground (Templeton et al, 2024). Current downhole sensing technologies are limited in their ability to withstand the extreme conditions expected in many target formations, let alone deliver continuous, high-resolution data (ibid). In these circumstances, without affordable, scalable monitoring solutions that can be deployed across diverse geological settings, operators will struggle to optimise production or demonstrate environmental compliance.

- **How will stimulated hydrogen integrate into existing hydrogen value chains in terms of purity, transport, and certification?**

Then comes the market integration question: What happens once the hydrogen is produced? As the cases of most detected hydrogen shows and vents of geologic hydrogen demonstrate, the composition of native hydrogen streams is rarely pure (Patonia et al, 2024). This is likely to be experienced with stimulated H_2 production, and impurities such as methane or hydrogen sulfide may require on-site purification before sale. Transport is another consideration: unlike centralised electrolysis plants sited near hydrogen hubs, stimulated production sites may be geographically dispersed, requiring flexible infrastructure solutions or co-located end users. Furthermore, regulatory frameworks have yet to clearly define how stimulated hydrogen should be certified and labelled, particularly regarding its carbon intensity when energy inputs for stimulation are considered. As practice shows, such uncertainties are likely to slow off-take agreements and complicate financing.

- **What scale and pace of deployment is achievable within permitting, supply chain, and market constraints**

Beyond these core issues, more important strategic questions about scale and rollout are also present. For instance, can the technology move beyond niche, site-specific projects into a globally significant contributor to hydrogen supply? How quickly can exploration, permitting, drilling, and commissioning be streamlined into a repeatable process? Will early adopters secure first-mover advantages, or will costs fall rapidly only after a critical mass of projects – as happened in shale gas and offshore wind? And perhaps most importantly, where will stimulated hydrogen fit in the broader market context as electrolyser costs fall, renewable energy deployment accelerates, and other emerging hydrogen pathways mature?

There are also broader system-level considerations. Could stimulated hydrogen reliably act as a baseload complement to variable renewable hydrogen, offering steady production that stabilises supply chains? How would it compete in a future where carbon pricing is stricter, green hydrogen subsidies are widespread, and end users demand full traceability of emissions? Conversely, could it find specialised roles – for instance, producing hydrogen near mining or industrial operations where reactive rock formations are already being accessed for other purposes?

- **What role will stimulated hydrogen play relative to other production pathways in the future energy mix?**

Even if technically and economically viable, stimulated hydrogen will compete with expanding green hydrogen from renewables as well as blue hydrogen where carbon capture is cost-effective and socially acceptable. Therefore, its role may range from serving as a stable baseload supply complementing variable renewable hydrogen to providing region-specific production where geology is favourable. Clear positioning in the broader energy landscape will influence both investment and policy support.

Ultimately, the commercialisation of stimulated geologic hydrogen hinges on reducing these unknowns to manageable, quantifiable risks. This will require not only technological innovation but also coordinated action between geoscientists, engineers, financiers, policymakers, and equipment manufacturers. Large-scale, multi-year pilot projects with transparent reporting will be indispensable for proving technical feasibility, establishing credible cost curves, and building the regulatory frameworks that enable safe, profitable deployment. Equally, only when robust energy and emissions balances are published will it be possible to judge whether stimulated hydrogen genuinely delivers on its ‘low-carbon’ promise. Without these answers, stimulated hydrogen will remain an intriguing but unproven idea.

Conclusions

Unlike natural hydrogen extraction, which depends on the rare coincidence of favourable geological conditions, stimulated approaches to geologic hydrogen production aim to deliberately engineer subsurface environments to generate hydrogen in situ. Laboratory studies and early field pilots suggest that engineered stimulation could achieve competitive production costs while avoiding the high energy demands of electrolysis or the carbon intensity of fossil-based routes. While several stimulation methods show promise, critical knowledge gaps remain around scalability, long-term yields, and economic competitiveness. The field is still at a very early stage, and even under optimistic assumptions, the first commercial-scale deployment is unlikely to occur within the next decade, with timelines of at least 10 years appearing realistic. This Energy Insight reveals the following key conclusions:

- **Stimulated geologic hydrogen production offers a promising alternative to exploration-dependent natural hydrogen extraction, with potential for low-carbon, cost-competitive output**

By creating favourable subsurface environments through engineered stimulation, developers can sidestep the rarity and unpredictability of large-scale native hydrogen accumulations. Laboratory and pilot-scale results suggest that such production could achieve both low carbon intensity and competitive costs, potentially below USD 1 per kg. These features position stimulated hydrogen as a potentially serious contender to green and blue hydrogen, particularly where geological conditions are favourable and renewable energy or CCS-based alternatives face scalability or cost barriers. However, these advantages remain theoretical until proven at commercial scale.

- **Key stimulation methods are currently at varying technology readiness levels (TRL 2-6), with Electrical Reservoir Stimulation and Advanced Weathering Enhancement leading in maturity and pilot deployment**

ERS and AWE stand out for their relative technical maturity and the ability to mimic well-characterised natural hydrogen-generating reactions. Field pilots have demonstrated operational feasibility and environmental advantages, such as lower water use and precise control over reaction zones. Other methods remain at earlier TRLs, facing barriers including high upfront drilling costs, environmental risks, slow production rates, or limited geological applicability. The diversity of approaches reflects both the complexity of subsurface hydrogen generation and the likelihood that multiple technologies will coexist, tailored to specific geological and market contexts.

- **Field evidence remains insufficient to confirm commercial-scale hydrogen yields, cost competitiveness, and long-term production sustainability**

Most existing cost and performance estimates rely on laboratory data or short-duration field trials, which do not capture the full energy inputs, maintenance requirements, and potential decline in production over time. Uncertainties in reaction longevity, reservoir permeability, and mineral passivation could undermine long-term viability. Without multi-year, transparent operational data, claims of sustained low-cost production remain speculative, limiting investor confidence and delaying market integration.

- **Geological setting selection is a critical determinant of success; repeatable, high-yield environments remain poorly characterised**

While ultramafic formations such as peridotites and serpentinites are prime candidates, performance varies significantly depending on mineralogy, temperature-pressure conditions, and fluid chemistry. The lack of a robust, standardised 'geological playbook' hampers efficient site selection and risk assessment. Improved geoscientific understanding will be essential for scaling the technology and avoiding costly mismatches between chosen sites and expected production outcomes.

- **Risk management and monitoring are prerequisites for public acceptance and regulatory approval**

Subsurface stimulation can alter geological and hydrological systems, potentially triggering seismic events or mobilising harmful substances. Public confidence will require transparent risk assessments, early stakeholder engagement, and robust, real-time monitoring of chemical, thermal, and structural changes in the subsurface. Current sensing technologies struggle under the extreme conditions expected, making the development of affordable, durable systems essential before large-scale rollout.

- **Market integration hinges on purity, logistics, and certification**

Stimulated hydrogen will likely require on-site purification to remove contaminants such as methane or hydrogen sulfide, while geographically dispersed production sites could pose transport challenges. Without clear certification frameworks – particularly for carbon intensity – market uptake may stall. Aligning production with existing infrastructure and international standards will be critical to building buyer confidence.

- **Competitiveness will depend on economics, policy, and strategic positioning**

If proven viable, stimulated hydrogen could serve as a stable baseload complement to intermittent renewable hydrogen or as a region-specific solution in areas with favourable geology. However, its role will be shaped by falling costs of alternative clean hydrogen production technologies, evolving carbon pricing, streamlined permitting, and targeted incentives that influence comparative economics with green and blue hydrogen.

- **Scaling requires multi-year, transparent demonstration projects**

Pilots must deliver credible cost curves, quantify environmental impacts, validate operational longevity, and establish best practices for site selection. Without this evidence, stimulated hydrogen will remain high-potential but unproven; with it, it could become a commercially scalable contributor to decarbonisation goals. On present evidence, this pathway should be regarded as a long-term option, with any meaningful contribution to hydrogen supply unlikely before the mid-2030s.

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