

Geothermal Hydrogen Generation Technologies A Comparative Synopsis

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This briefing document provides a detailed synopsis of three emerging geothermal hydrogen generation technologies: **(1) In Situ Geothermal Hydrogen Generation**, **(2) SOEC-Coupled Geothermal Hydrogen Generation**, and **(3) Natural (Geologic) Hydrogen**. Each section outlines the technology's principles, current activity, cost considerations, market readiness, and key initiatives needed to advance its development.

Introduction: Unlocking U.S. Hydrogen Potential through Geothermal Innovation

As global competition intensifies for leadership in clean hydrogen production, the United States has a strategic opportunity to harness its vast and diverse geologic resources to produce hydrogen in new, cost-effective, and carbon-free ways. This research package explores three emerging geothermal hydrogen generation technologies that can complement and strengthen America's hydrogen strategy by tapping into the Earth itself as both a chemical reactor and an energy source.

What This Research Covers

This document provides technical and strategic synopses of three distinct geothermal hydrogen pathways:

1. **In Situ Geothermal Hydrogen via Water-Rock Reactions**
Hydrogen is generated underground by injecting water into iron-rich geothermal formations, triggering geochemical reactions such as serpentinization that naturally split water into hydrogen and mineral byproducts. No fossil fuels or electrolysis are required, and the process is exothermic and potentially self-sustaining.
2. **SOEC-Coupled Geothermal Hydrogen Production**
High-temperature solid oxide electrolysis cells (SOECs) are powered and thermally integrated with geothermal energy to electrolyze steam with high efficiency and round-the-clock reliability. This approach is already being piloted in Japan, Indonesia, and Iceland.
3. **Natural (Geologic) Hydrogen Extraction**
Naturally occurring hydrogen accumulations—formed over geologic time through water-rock reactions and radiolysis—can be tapped similarly to natural gas. Early exploration in the U.S. (Kansas, Nebraska, Minnesota) and abroad suggests the potential for large-scale, low-cost, naturally replenishing hydrogen reservoirs.

Importance to the United States

- **Energy Security:** These technologies rely on domestic, geology-based resources—reducing U.S. reliance on imported hydrogen carriers or materials for electrolysis systems.
- **Economic Competitiveness:** Preliminary estimates suggest in situ and natural hydrogen could be produced at or below \$1/kg—meeting the DOE Hydrogen Shot target while creating a new extractive hydrogen industry rooted in U.S. know-how.
- **Infrastructure Leverage:** Many methods can repurpose legacy oil, gas, and geothermal infrastructure, supporting workforce transition and lowering deployment costs.
- **Global Leadership:** By investing early in geothermal hydrogen R&D, the U.S. can lead in a frontier hydrogen domain not yet dominated by any nation.

As DOE seeks to diversify hydrogen production pathways and drive costs down, geothermal hydrogen technologies—now moving from theory to field validation—offer a high-reward opportunity to expand clean hydrogen supply using America's unique geology and technical expertise.

In Situ Hydrogen Generation via Geothermal Water Injection

Briefing Synopsis Introduction

In situ hydrogen generation in geothermal formations is an emerging **carbon-free** production pathway that leverages natural water–rock reactions deep underground. The concept involves injecting water into hot, iron-rich rock formations (such as ultramafic or mafic geology) to trigger geochemical reactions that release molecular hydrogen (H₂).

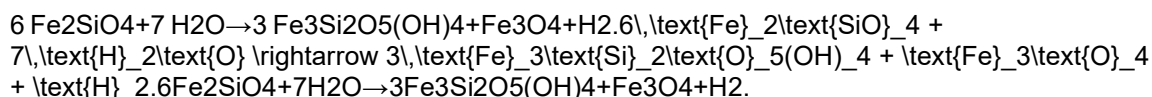
This approach produces “white” or geologic hydrogen without fossil fuel feedstocks or electrolysis, offering a potentially low-carbon and low-cost hydrogen source [mining.comgeoscientistonline](https://www.mdpi.com/geoscientist/online). While naturally occurring subterranean hydrogen has been observed (e.g. in ultramafic ophiolite sites and hydrothermal systems), engineered *in situ* generation aims to stimulate and scale up these processes for clean energy production.

This synopsis outlines the technology principles, current R&D status, economics, market readiness, and key initiatives needed to advance in situ geothermal hydrogen production.

Technology Basics and Geochemical Principles

Geochemical Reaction Mechanisms: The primary mechanism for in situ hydrogen generation is **serpentinization** – a well-known reaction in which water interacts with iron-bearing silicate minerals (common in ultramafic rocks) to form serpentine minerals and hydrogen gas. For example, when water infiltrates olivine-rich rocks (peridotite), olivine is converted into serpentine (a hydrated magnesium-iron silicate) and magnetite (iron oxide), releasing H₂ in the process [mdpi.commdpi.com](https://www.mdpi.com/mdpi.com).

A simplified representation is the oxidation of ferrous iron (Fe²⁺) by water to ferric iron (Fe³⁺) (in magnetite or other oxides), which splits water and yields H₂ [mdpi.com](https://www.mdpi.com). Equation (1) below illustrates this chemistry:



Above: Olivine (Fe₂SiO₄) + water produces serpentine [Fe₃Si₂O₅(OH)₄] + magnetite (Fe₃O₄) + hydrogen [mdpi.com](https://www.mdpi.com).

Schematic of subsurface hydrogen generation processes. Water infiltrating down faults reacts with iron-rich rocks (e.g., olivine in mantle peridotite) to produce H₂ (blue bubbles). In *serpentinization* zones (labeled 2), olivine + H₂O yields serpentine and H₂. This hydrogen can migrate upward, sometimes seeping at surface seeps or accumulating under cap rocks. Other processes like natural radiolysis (1) in basement rocks can also generate H₂, while some H₂ may be consumed abiotically or by microbes (5,6). *Image adapted from Science/DOE.* [mdpi.commdpi.com](https://www.mdpi.com/mdpi.com)

Geothermal Conditions: These reactions are favored in geothermal environments where elevated temperatures and pressures accelerate water–rock interaction. Serpentinization is exothermic (releasing heat) and occurs over a broad temperature range (~50–400 °C) [mdpi.commdpi.com](https://www.mdpi.com/mdpi.com). Higher temperatures generally increase reaction rates and H₂ output, up to the stability limit of olivine (~400 °C) [mdpi.commdpi.com](https://www.mdpi.com/mdpi.com). Sufficient pressure (depth) also promotes more complete reactions by keeping water in contact with rock and enhancing hydrogen solubility [mdpi.com](https://www.mdpi.com).

These conditions are naturally met in some hydrothermal systems and can be engineered via deep injection wells in enhanced geothermal systems (EGS). Notably, *mafic* rocks (like basalts) can also produce hydrogen through similar iron oxidation processes, though typically in smaller quantities than ultramafic rocks.

Recent laboratory experiments have confirmed basalt–water reactions generating H₂ under simulated sequestration conditions [research.ed.ac.uk](https://research.ed.ac.uk/research/research.ed.ac.uk), reinforcing that a range of rock types in geothermal settings can yield hydrogen when water is introduced. In these reactions, any oxygen released tends to be immediately captured by oxidizing the rock minerals, leaving hydrogen gas as the free product [patents.google.com](https://patents.google.com/patents/google.com).

No Fossil or Biological Inputs: Crucially, the in situ approach relies purely on inorganic chemistry – no hydrocarbons are involved, and the process is distinct from biologically assisted hydrogen generation. Natural hydrogen systems often must contend with subsurface microbes that can consume H₂ (e.g. methanogens converting H₂ to methane). Engineered systems will consider strategies to inhibit microbial uptake nrel.gov, ensuring that the hydrogen produced geochemically remains available for collection. Overall, the underlying science leverages Earth’s own hydrogen-producing reactions (sometimes termed “white hydrogen” generation) in a controlled manner to supply a carbon-free fuel [geoscientist.online](https://geoscientist.online/geoscientist.online).

Current Activity and Research Status

Growing R&D and Exploration: Until recently, geologic hydrogen was little-known, but activity has accelerated markedly. As of 2023, on the order of 40 companies worldwide are exploring natural hydrogen resources, up from just a handful a few years prior [mining.com](https://mining.com/mining.com). These include ventures in the United States, Australia, Europe, and Africa targeting subsurface hydrogen accumulations (“gold” or white hydrogen). For example, natural hydrogen seeps discovered in Mali (Bourakébougou) have been successfully tapped to run electricity generators, proving that hydrogen can accumulate in commercially useful quantities [geoscientist.online](https://geoscientist.online/geoscientist.online).

In the US, exploration companies are drilling in regions like Kansas/Nebraska along the ancient Midcontinent Rift, where geologic conditions suggest abundant iron-rich rocks and past hydrogen shows. Notably, wells in Kansas have encountered hydrogen concentrations above 90% in gas samples upstreamonline.com, and active drilling programs are underway to delineate hydrogen-bearing structures (e.g. the HyTerra Nemaha project). These efforts mark the first generation of field trials aimed at *discovering or stimulating* hydrogen reserves analogous to natural gas exploration.

Government and Academic Initiatives: Recognizing the potential, the U.S. Department of Energy (DOE) launched dedicated research support in 2024. In February 2024, DOE’s ARPA-E announced \$20 million for 16 projects across 8 states to “accelerate the natural subsurface generation of hydrogen” via stimulated geologic processes and reservoir management [hydrogen.energy.gov](https://hydrogen.energy.gov/gasproductionrules.mn.gov). The selected teams – spanning universities, national labs, and startups – are investigating methods to enhance hydrogen yields from various formations.

For instance, a project led by Texas Tech University (with partners NREL and others) is studying how to stimulate hydrogen production from iron-rich mafic and ultramafic rocks using chemical and mechanical techniques [nrel.gov](https://nrel.gov/nrel.gov). Laboratory microcosm experiments are simulating water injection into different rock types, measuring hydrogen release rates and exploring catalysts to boost reaction efficiency [nrel.gov](https://nrel.gov/nrel.gov).

Other ARPA-E projects focus on hydrogen reservoir management, i.e. how to detect, collect, and sustain hydrogen flows in the subsurface once generated [pv-magazine.com](https://pv-magazine.com/pv-magazine.com). This first wave of federally funded research is building foundational knowledge on reaction kinetics, optimal temperatures, and strategies to scale up in situ hydrogen production.

International research is also active. The first international summit on natural hydrogen (H-Nat, 2021) highlighted case studies from Africa, North America, and Europe [geoscientist.online](https://geoscientist.online/geoscientist.online), and countries like France, Australia, and Brazil have launched geologic hydrogen exploration programs. Geologic surveys (e.g., USGS and BRGM in France) are mapping ultramafic rock distributions and using surface indicators (such as “**fairy circles**” barren spots associated with hydrogen seeps) to pinpoint prospects [geoscientist.online](https://geoscientist.online/geoscientist.online).

On the engineering front, a few pilot well projects are in planning or early execution phases: for example, in Australia, a collaboration is testing hydrogen production in a deep borehole intersecting a known natural hydrogen occurrence, and in the United States the U.S. Air Force is evaluating a geothermal-hydrogen pilot (in Texas) as part of a base energy resiliency project fuelcellsworks.com/wpafb.af.mil. While no large commercial operation exists yet, **proof-of-concept demonstrations** at small scale are beginning to validate the feasibility of extracting hydrogen from suitable underground settings.

Alkaline spring in Oman (Bahla area) where serpentinization generates hydrogen naturally. The whitish mineral deposits and high pH water result from water reacting with peridotite in the subsurface, producing hydrogen gas that emerges with the spring. Such natural sites inspire engineered in situ hydrogen production, as they confirm that substantial hydrogen can be generated underground mining.com.

Total Cost of Ownership (TCO) Considerations

Infrastructure Requirements: In situ hydrogen generation combines aspects of geothermal energy wells and natural gas production infrastructure. A basic system would require deep injection wells (to deliver water into the target formation) and production wells to bring hydrogen (and co-produced fluids) to the surface. Drilling costs can be significant – similar to drilling for geothermal or oil & gas – potentially several million dollars per well depending on depth and rock hardness.

Enhanced geothermal techniques (e.g. directional drilling and reservoir stimulation via hydrofracturing) may be employed to increase the contact area between water and rock, improving hydrogen yields wpafb.af.mil/wpafb.af.mil. This adds upfront cost for reservoir creation but is crucial for scalability. Surface facilities would include pumps and compressors, water handling systems (to inject water and circulate fluids), gas–water separators, and hydrogen purification units. Novel downhole tools might also be used, such as hydrogen-selective membranes placed in the well to filter hydrogen out of the hot fluid stream patents.google.com/patents.google.com, reducing the need to bring large volumes of water to the surface.

Operational Costs: Once the wells and facilities are in place, operating costs center on pumping power (for water injection and fluid circulation), maintenance of wells (workovers, corrosion management), and hydrogen gas processing. Fortunately, the “fuel” for hydrogen generation – water and the rock’s mineral content – is abundantly available and does not have to be purchased like natural gas or coal. Water may need pretreatment to avoid scaling, and if freshwater is used there could be sourcing costs (or seawater/brine could be used in coastal sites to avoid straining potable supply).

Energy is required to pressurize and inject water, but much of the reaction enthalpy comes from geothermal heat and the exothermic chemistry itself. This means the energy return could be favorable. One possible co-product is heat: serpentinization releases heat, and the produced hot water/steam might be usable for power generation or to help drive turbines, improving the overall economics (essentially a hybrid geothermal-hydrogen plant). Operators would also incur costs for monitoring, safety systems (hydrogen sensors, explosion-proof equipment), and managing any byproducts (for instance, minerals that precipitate in the reservoir or borehole).

Cost Competitiveness: Early analyses suggest that geologic hydrogen, if attainable, could be extremely cost-competitive with other hydrogen production methods. Because in situ production does not require electricity (as electrolysis does) or natural gas feedstock (as steam methane reforming does), the direct production cost per kilogram hydrogen could be very low – on the order of \$1 or less. In fact, pilot projects and models have estimated natural hydrogen extraction costs in the range of \$0.5–1.0 per kg mining.com/geoscientist.online.

This contrasts with green hydrogen from renewables (currently \$3–8 per kg) and even “grey” hydrogen from unabated natural gas (~\$1–2 per kg) geoscientist.online. The low cost projection is largely due to the minimal energy input required once a self-sustaining reaction is established underground. However, these figures are speculative until demonstrated at scale – they assume robust hydrogen flows and long-lived wells.

Total cost of ownership must account for the full project lifecycle: high upfront drilling investment, exploration risk (not every well will find or generate hydrogen in quantity), and eventual decommissioning costs. If a single engineered reservoir could produce a steady stream of hydrogen for many years, the capital costs would be amortized over a large output, yielding very low unit costs. On the other hand, if reaction rates or flows are lower than expected, more wells would be needed, driving up costs. Scalability will hinge on how large an area can be swept by injected water and how effectively the hydrogen can be collected.

Nevertheless, the potential for low TCO is a major driver of interest – a successful project could produce clean hydrogen at a fraction of the cost of electrolysis, with **minimal ongoing fuel cost** (since nature does the chemical work).

Scalability and Logistics: From a scalability perspective, in situ hydrogen farms would resemble geothermal fields or gas fields, possibly covering wide geographic areas with well pads and surface pipelines. This necessitates securing land and mineral rights and could involve long pipelines to transport the produced hydrogen to end users or central hubs. If the resource is remote, transportation adds to the effective cost (though hydrogen could be converted to ammonia or other carriers on site if needed).

The scalability is ultimately tied to geology – regions with extensive ultramafic rock (such as ophiolite belts or volcanic provinces) could support multiple injection sites. One advantage is that depleted oil/gas reservoirs or other deep formations might be repurposed for hydrogen generation, leveraging existing infrastructure.

TCO considerations, therefore, include not just the raw production cost but also infrastructure build-out for distribution and storage. Assuming supportive geology, the modular nature of drilling wells means production could be ramped up by adding more well pairs, subject to reservoir management to avoid interference. In summary, while exact costs remain to be proven, the in situ approach has an inherently attractive cost structure: no expensive feedstock, continuous generation, and potential co-production of heat, offset by high initial investment and geological uncertainty.

Market Readiness and Commercialization Prospects

Technology Readiness Level (TRL): Geologic hydrogen generation via water injection is currently at a very early stage of development – roughly TRL 2–3 (concept formulated and proof-of-concept in lab) and moving toward TRL 4–5 as field experiments commence. There are no commercial-scale projects in operation yet. The U.S. government’s 2024 ARPA-E program represents the first federally funded research effort on this technology [nrel.gov](https://www.nrel.gov), highlighting that it is still in R&D.

Small-scale demonstrations, like the Mali hydrogen well powering a village or ongoing test wells in Kansas, serve as pilot demonstrations (TRL 5) of natural hydrogen extraction, but these are limited in scope (a few kilograms of H₂ per hour). To reach TRL 6–7, the next step is integrated field pilots that include injection, production, and surface handling of hydrogen in one system.

Enthusiasm is growing: exploration companies have raised venture funding, and some oil & gas companies are beginning to look at “hydrogen from rock” as a diversification play. Still, the technology can be considered in its *infancy* relative to mature hydrogen production methods.

Current Barriers: Several challenges must be overcome before in situ hydrogen can be commercialized:

1. **Uncertain Resource Density:** It is not yet known how much hydrogen can be generated per well or per formation on a sustainable basis. Natural hydrogen seeps are often diffusive and low-rate. Engineering efforts aim to greatly accelerate generation, but real-world yields remain to be proven.
2. **Kinetics and Reactivity:** The speed of serpentinization or related reactions could be a limiting factor – if it takes years to produce meaningful H₂ quantities, the process may not

be economic. R&D is ongoing to identify catalysts or stimulation methods (heat, fracturing, chemical additives) to increase reaction rates.

3. **Hydrogen Recovery:** Capturing the hydrogen before it is diluted or consumed is tricky. H_2 is a small, mobile molecule and can be partly lost to side reactions or through escape pathways. If microbes are present in the subsurface, they can consume hydrogen (turning it into methane or water), effectively stealing the product. Thus, isolation of the reaction zone or biocide measures might be needed [nrel.gov](https://www.nrel.gov).
4. **Materials and Safety:** Hydrogen is notorious for causing embrittlement in steel pipes and casings. Geothermal conditions add high temperature and corrosion potential (especially if H_2S or CO_2 are also present from rock reactions). Developing wells and surface equipment that can handle hot, pressurized hydrogen–water mixtures without leaks or failures is essential. Safety systems for preventing ignition of hydrogen will also be required.
5. **Regulatory and Legal Framework:** The concept of extracting native hydrogen raises regulatory questions – many jurisdictions don't yet define hydrogen as a subsurface resource. In the U.S., states like Minnesota only recently enacted legislation to allow leasing and permitting for geologic hydrogen exploration [gasproductionrules.mn.gov](https://www.gasproductionrules.mn.gov). Clear rules on resource rights, environmental protection, and well permitting will need to catch up to the technology. Additionally, environmental assessments must consider any induced seismicity from injection (as with geothermal projects) or potential water contamination issues.

Commercialization Outlook: If ongoing research and pilots demonstrate viable hydrogen flow rates and manageable costs, in situ hydrogen could progress to commercial trials within the next 5–10 years. Early deployment might occur in locations with known favorable geology – for example, peridotite-rich formations on land (Oman ophiolite, U.S. midcontinent rift, Western Australian cratons, etc.) or perhaps in deep offshore basalt reservoirs. Initial projects may be small (~hundreds of kilograms to a few tons of hydrogen per day) selling hydrogen for high-value uses (such as fuel cell vehicle fueling or industrial trials). As confidence grows, larger scale operations (hundreds of tons per day) could be pursued, potentially as part of the DOE's Hydrogen Earthshot goal of \$1 per 1 kg in 1 decade.

Key to commercialization will be **risk reduction**: proving that wells can produce for long durations without depleting or needing frequent restimulation, and that the process is indeed as clean as expected (life-cycle emissions are minimal). On the emissions point, geologic hydrogen is very attractive – if no fossil fuels are involved, the only significant emissions might come from drilling and pumping (which could be mitigated by using renewable-powered equipment). Estimates show a carbon intensity well under 1 kg CO_2 per kg hydrogen [mining.com](https://www.mining.com), far below even blue hydrogen. This means projects could qualify for incentives like the U.S. hydrogen production tax credit (which offers up to \$3/kg for low-carbon hydrogen) [mining.com](https://www.mining.com), boosting economic viability.

In summary, market readiness is nascent: the technology has enormous promise (potentially game-changing cost and carbon profile [mining.com](https://www.mining.com)) but must navigate through technical and operational challenges typical of frontier energy technologies. Over the coming few years, we expect to see a transition from laboratory and exploration findings to the first integrated pilot plants, which will inform whether in situ geothermal hydrogen can become a commercial reality contributing to clean hydrogen supply by the 2030s.

Key Initiatives to Advance the Technology

To accelerate progress, several strategic project initiatives are recommended (some already underway) that would significantly advance in situ hydrogen generation toward commercial readiness:

1. **Integrated Field Pilot Demonstration:** A dedicated field pilot project in a high-potential geologic setting is crucial to validate this technology at scale. This would involve drilling a pair of wells (injection and production) into an ultramafic-rich formation, circulating water, and producing hydrogen gas over an extended period. Monitoring sensors would track hydrogen production rate, pressure, temperature, and geochemical changes. Such a pilot – ideally supported by a government–industry consortium – would provide real-world data on achievable hydrogen flow rates and help optimize well design. (Status: Proposed – no full-scale pilot has been completed yet. Design work and site selection could begin now, leveraging sites with known hydrogen seeps or active serpentinization.)
2. **Enhanced Reaction R&D (Stimulation Techniques):** Ongoing R&D should continue to focus on maximizing the hydrogen output from rock–water reactions. This includes laboratory experiments and numerical modeling to test stimulation methods such as: elevating temperature/pressure (using deeper or hotter wells), hydraulic fracturing to increase rock surface area, injecting chemical catalysts or optimized fluid mixtures, and even using controlled carbonation reactions to generate favorable conditions. For example, the ARPA-E project led by Texas Tech/NREL is exploring mechanical (fracture) and chemical stimulation of peridotite to boost H₂ yields nrel.gov/nrel.gov. Expanding such research – possibly through a field testbed in a mine or dedicated rock laboratory – will refine the best practices for prompting hydrogen generation quickly. Success in this area would directly improve the economics (more H₂ per well).
3. **Hydrogen Collection & Separation Technology:** Developing efficient methods to extract and purify hydrogen in situ will greatly advance commercial viability. One initiative is to design **downhole hydrogen separators** – for instance, special ceramic or metal membranes placed in the wellbore that allow H₂ to pass while blocking water patents.google.com. This could allow hydrogen (or even protons) to be pumped to the surface directly, leveraging concepts from fuel cell technology in reverse patents.google.com. DOE or industry pilot projects to test H₂-selective membranes or novel lift systems (like gas lift or submersible pumps adapted for hydrogen service) in a geothermal well would be very impactful. Additionally, surface processing skids tailored for geologic hydrogen (separating H₂ from any N₂, CH₄, or other gases, and drying it) need to be prototyped. These engineering developments ensure that once hydrogen is generated down below, it can be efficiently brought above ground at high purity ready for use or pipeline injection.
4. **Resource Mapping and Geologic Characterization:** A broad initiative led by geological surveys and research institutions should map and characterize the most promising hydrogen-generating environments. This means funding geophysical surveys, exploratory drilling, and geochemical characterization in areas with suitable bedrock (e.g. large ultramafic bodies, basaltic rifts, and old cratonic faults). The U.S. Midcontinent Rift System, for example, has been identified by USGS as highly prospective for geologic hydrogen gasproductionrules.mn.gov. By drilling stratigraphic test wells and sampling gas/fluid inclusions, researchers can delineate “sweet spots” where in situ projects would have the best chance of success. Such an initiative, possibly part of a DOE Geothermal or Hydrogen program, would reduce uncertainty by providing data on hydrogen generation rates in different rock types and help target future pilot sites. International collaboration (sharing data from Mali, Oman, etc.) can augment this knowledge base. Essentially, establishing a geologic hydrogen atlas and reaction-rate database will guide investment and prevent wasted effort in unproductive sites.
5. **Regulatory and Market Development Programs:** To support commercialization, parallel efforts in policy and market development are needed. One key initiative is working with regulators at federal and state levels to establish a clear regulatory framework for in situ hydrogen. This involves updating mining and gas laws to recognize hydrogen as a resource, setting safety standards for hydrogen wells, and streamlining permits for pilot projects. Minnesota’s recent legislation creating a framework for geologic hydrogen exploration is an early example gasproductionrules.mn.gov. The DOE Hydrogen Fuel Cell Technologies Office could convene a task force with regulators, industry, and environmental experts to develop best practice guidelines and address environmental concerns proactively. Additionally, market pull mechanisms (like the

Hydrogen Hubs program or production tax credits) should explicitly include geologic hydrogen pathways if low-carbon criteria are met. By earmarking some funding or offtake agreements for a geologic H₂ project, DOE can de-risk the first movers. Finally, public-private partnerships for knowledge sharing (similar to DOE's National Labs working with geothermal companies) will significantly advance the know-how. These "soft" initiatives ensure that when the technology is technically ready, there is a supportive ecosystem to rapidly scale deployment.

Each of the above project initiatives tackles a critical piece of the puzzle – from proving the concept in the field, to improving efficiency, to building the infrastructure and regulatory environment. Together, they form a roadmap for taking in situ hydrogen generation via water injection from experimental stages today to a viable component of the clean energy portfolio in the near future. The U.S. Department of Energy and its partners have a pivotal role to play in driving these efforts forward, capitalizing on the momentum of recent ARPA-E projects and global interest in natural hydrogen. With sustained R&D and strategic demonstrations, geothermal-based hydrogen generation could transition from a novel idea to a deployable clean hydrogen solution that contributes to energy security and climate goals.

SOEC-Coupled Geothermal Hydrogen Generation Technology Basics and Underlying Principles

SOEC geothermal hydrogen generation refers to the use of geothermal energy (heat and electricity from Earth's geothermal resources) to drive water electrolysis for hydrogen production, specifically using **Solid Oxide Electrolysis Cells (SOECs)**. An SOEC is a high-temperature electrolyzer that operates at ~700–850 °C, using a solid ceramic electrolyte to split steam into hydrogen and oxygen with high efficiency. By coupling SOECs with geothermal sources, two advantages are realized:

1. **Renewable Power Supply:** Geothermal power plants provide a continuous, dispatchable source of electricity (and sometimes mechanical work), which can be used to run the electrolysis process. This means hydrogen can be produced 24/7 from a clean energy source, unlike solar or wind which are intermittent.
2. **Thermal Integration:** Geothermal steam or hot water can supply some or all of the heat required to raise water to SOEC operating temperature. This **direct use of geothermal heat** can improve overall efficiency. In a conventional electrolyzer, all the energy input is electrical, whereas an SOEC can take a portion as thermal energy. By feeding pre-heated steam from a geothermal well into the SOEC, the electrical energy needed per kg of H₂ is reduced. Toshiba, for example, reports that its SOEC technology can improve hydrogen production efficiency by up to 30% compared to low-temperature electrolyzers [toshiba.com](https://www.toshiba.com), largely due to operating with high-temperature steam. Using “free” geothermal heat to provide that temperature can further enhance efficiency and lower cost.

In practical terms, a geothermal-SOEC system might work as follows: A geothermal well produces high-pressure steam (often in the range of 150–300 °C at conventional hydrothermal sites, or higher if it's a high-enthalpy field). This steam is first run through a turbine to generate electricity (geothermal power plant). A portion of the steam (either extracted from the turbine or from secondary low-pressure steam that is otherwise wasted) is diverted to an SOEC unit as feedstock thinkgeoenergy.com. The SOEC unit, kept at operating temperature by resistive heating and the hot steam input, electrolyzes H₂O into H₂ and O₂.

The required electricity is supplied by the geothermal generator itself, essentially creating a self-contained “geothermal hydrogen plant.” Any unused steam or low-grade heat can potentially be recycled within the system (for example, to preheat inlet water). The oxygen by-product, which comes out hot, could be vented or utilized (e.g. for nearby industrial processes or even reinjected into geothermal wells to stimulate production).

This integration of geothermal with hydrogen production is sometimes described as converting geothermal energy into chemical energy (hydrogen) – effectively a form of Power-to-Gas using geothermal power. It is distinct from simply powering a regular electrolyzer with geothermal electricity in that it actively uses the thermal component via SOEC. This makes it a highly efficient route:

Laboratory and pilot SOEC systems have demonstrated energy efficiency in the range of 80–90% (LHV basis) when waste heat is utilized, significantly higher than the ~60–70% efficiency of ambient-temperature electrolysis [toshiba.com](https://www.toshiba.com). Moreover, geothermal plants often have **excess steam** or off-peak capacity (especially in regions where electricity demand is variable); producing hydrogen offers a way to monetize that excess without carbon emissions thinkgeoenergy.com.

In summary, SOEC geothermal hydrogen generation is the convergence of advanced electrolyzer technology and geothermal renewable energy. It harnesses geothermal steam both as a heat source and an electricity source to split water, yielding green hydrogen. The underlying principle is improving hydrogen yield per unit of input energy by leveraging the readily available heat from the Earth, thus lowering the electricity requirement for hydrogen production thinkgeoenergy.com [toshiba.com](https://www.toshiba.com).

Current Level of Activity (Deployments, Pilots, Research)

The concept of geothermal-powered electrolysis is being explored through several pilot projects and research initiatives worldwide, though it is still emerging. Key activities include:

- **Japan (NEDO Geothermal Hydrogen Project)** – A notable initiative is underway in Japan's Kyushu region. In 2022, Toshiba Energy Systems & Solutions and Kansai Electric Power (KEPCO) launched a NEDO-funded project to study hydrogen production using *unused geothermal steam* in Oguni-machi, Kumamoto thinkgeoenergy.com. This project (July 2022 – March 2023) designed an integrated system where geothermal steam that would otherwise be wasted is used to produce hydrogen via a Toshiba-designed SOEC unit thinkgeoenergy.com. Toshiba's role included engineering the layout of the SOEC hydrogen production equipment and a steam turbine-generator that supplies electricity to it thinkgeoenergy.com.

The goal was to assess how much hydrogen could be produced from the available steam and to evaluate hydrogen use cases locally. While results have not been fully disclosed publicly, this study represents a first-of-a-kind engineering analysis of coupling a geothermal plant with high-temperature electrolysis. It is viewed as a step toward a future business model of distributed "geothermal hydrogen" production in Japan thinkgeoenergy.com. Following the study, the consortium aimed to establish if stable, low-cost hydrogen can be generated and possibly move to a demonstration phase. The project highlights Japan's interest in leveraging its geothermal resources (which are abundant, especially in Kyushu and Tohoku) for clean hydrogen generation thinkgeoenergy.com.

- **Indonesia (Pertamina-TEPCO Joint Pilot)** – Indonesia, home to extensive geothermal operations, has started pursuing green hydrogen at geothermal sites. In 2023, Pertamina Geothermal Energy (PGE) and Tokyo Electric Power Company (TEPCO) announced a joint project to develop cost-effective hydrogen production using a geothermal power plant in Lahendong, North Sulawesi thinkgeoenergy.com. Supported by NEDO (Japan), this collaboration plans to install hydrogen production equipment at an existing geothermal facility. Specifically, a pilot targeting 100 kg H₂ per day output in PGE's Ulubelu geothermal area is under development thinkgeoenergy.com.

This pilot will use geothermal electricity to run electrolysis (likely involving high-temperature electrolysis expertise from Japan) and will examine hydrogen transportation solutions thinkgeoenergy.com. The involvement of a Japanese utility and a major Indonesian geothermal operator underscores a real-world push: the first hydrogen from this project would demonstrate the viability in a developing country context. As of early 2025, reports indicate the project is moving forward, with site visits by Japanese and Indonesian officials thinkgeoenergy.com and broader plans to integrate hydrogen or ammonia production into new geothermal projects in Indonesia thinkgeoenergy.com. This is among the world's first field demonstrations of geothermal-to-hydrogen at a meaningful scale.

- **Iceland and Northern Europe** – Iceland has been a pioneer in geothermal hydrogen concepts, given its 100% renewable grid (geothermal and hydro). As early as 2018, Iceland's ON Power launched an experimental hydrogen production station at the Hellisheiði geothermal power plant, near Reykjavík thinkgeoenergy.com. A modest-capacity alkaline electrolyzer (≈750 kW) was installed, using geothermal electricity to produce hydrogen for local fuel cell vehicles ptx-hub.org thinkgeoenergy.com. This project marked one of the first instances of geothermal energy powering hydrogen fuel supply (with H₂ dispensed at a fueling station by October 2018) thinkgeoenergy.com. Building on that, plans have grown more ambitious: At the Reykjanes geothermal plant, a project was announced in 2021 to produce green methanol from geothermal power and CO₂. UK-based Hydrogen Ventures Ltd. intends to build a plant next to the 100 MW Reykjanes geothermal power station, initially installing ~30 MW of electrolysis (using geothermal electricity) to generate hydrogen for methanol synthesis thinkgeoenergy.com. The first phase, costed at over €100 million, will produce methanol with hydrogen derived entirely from geothermal power, with a scale-up in phase two thinkgeoenergy.com. In a related venture, an Icelandic firm (GreenFuel in partnership with Atome Energy) is planning a

30 MW SOEC-based hydrogen/ammonia facility at the Theistareykir geothermal site by 2023–2025 [ptx-hub.org](https://www.ptx-hub.org). These projects are turning Iceland's geothermal riches into exportable e-fuels via hydrogen. Northern Europe is watching closely; Iceland's successes could be replicated in regions like Norway's geothermal projects or Eastern Europe (wherever moderate geothermal resources exist).

- **Other Regions – Kenya has included geothermal hydrogen in its strategic plans.** Kenya Electricity Generating Company (KenGen) issued an RFP in 2022 for a feasibility study on green hydrogen, ammonia, and fertilizer production using the Olkaria geothermal field [gh2.org](https://www.gh2.org). This initiative could lead to a pilot plant at Olkaria producing hydrogen and ammonia, aimed at decarbonizing fertilizer use in Kenya.

In the United States, geothermal-rich states (Nevada, California, Utah) are exploring synergies with hydrogen: the DOE's Geothermal Technologies Office and Hydrogen and Fuel Cell Office have begun joint discussions on "Hydrogen from Geothermal" as part of the Hydrogen Shot, though no dedicated pilot has been publicly announced as of 2025. In Europe, the EU's Horizon Europe program has recognized geothermal hydrogen in its calls (e.g. a 2023 call for proposals on "geothermal energy for hydrogen production" to combine renewable heat with electrolysis was noted in a PTX roadmap [ptx-hub.org](https://www.ptx-hub.org)).

Overall, current activity is characterized by pilot-scale demonstrations and feasibility studies rather than full commercial deployments. At least two pilot plants (Japan and Indonesia) are in progress to produce hydrogen using geothermal energy and SOEC/advanced electrolysis, each in the ~100 kg/day range [thinkgeoenergy.com](https://www.thinkgeoenergy.com). Iceland has operational experience with smaller-scale production and is constructing larger facilities (tied to fuel synthesis) [thinkgeoenergy.com](https://www.thinkgeoenergy.com). Academic research is also ongoing to model integrated geothermal-hydrogen systems for performance and cost (e.g., studies propose models for using low-temperature geothermal brines with electrolysis [sciencedirect.com](https://www.sciencedirect.com) onlinelibrary.wiley.com). Importantly, all these efforts treat geothermal hydrogen as a way to firm up green hydrogen supply (since geothermal provides baseload power) and utilize otherwise wasted heat or CO₂ streams (as in Iceland's e-methanol concept [thinkgeoenergy.com](https://www.thinkgeoenergy.com)).

Estimated Total Cost of Ownership (TCO) and Scalability

Capital Infrastructure: A geothermal-SOEC hydrogen facility requires significant up-front investment in both geothermal and electrolysis assets. On the geothermal side, capital costs include drilling production wells, steam gathering systems, and the power plant (turbines, separators, etc.) unless one ties into an existing geothermal plant. Often, early projects piggyback on existing plants to avoid these costs (e.g., using surplus steam from an operating plant).

On the hydrogen side, costs include the SOEC stacks, power electronics, hydrogen drying/compression, and storage or pipeline facilities for the product hydrogen. SOEC systems are currently more expensive per kW than conventional PEM or alkaline electrolyzers, as the technology is less mature and manufactured in smaller volumes. However, their higher efficiency can offset some of the cost in operations.

For perspective, the 30 MW Reykjanes phase-1 plant (electrolyzers plus methanol synthesis unit) was estimated at €100 million [thinkgeoenergy.com](https://www.thinkgeoenergy.com). A large fraction of that is the electrolyzer and chemical plant. Standalone, electrolyzer CAPEX can range from \$1,000 to \$2,000 per kW for SOEC at present (expected to decrease with scale and learning). Geothermal plant CAPEX varies widely by resource quality; a ballpark is \$3–5 million per MW for new geothermal capacity. If using an existing plant's steam, that cost is dramatically reduced.

Operational Costs: The biggest factor in hydrogen production cost is the electricity cost. Geothermal offers a stable electricity price, often in the range of \$0.05 to \$0.10 per kWh for well-established fields. This is competitive with wind/solar in many regions (though not as low as the very cheapest solar). Because SOEC units can achieve high efficiency, the electricity required to produce 1 kg of H₂ might be

on the order of 40–45 kWh (versus ~50–55 kWh for PEM electrolysis at lower temperature). At \$0.06/kWh, the electricity cost per kg H₂ would be ~\$2.4. There is also a thermal energy input, but in geothermal integration this heat is essentially a free by-product of the resource. Water supply is another operational cost consideration – demineralized water is needed for electrolysis. Geothermal condensate could potentially be used, which would reduce the need to import water (especially important in arid geothermal locations).

Maintenance of SOEC stacks is a notable OPEX: high-temperature operation leads to stack degradation over time. Stack lifetime is a key driver of cost; current SOEC lifetimes are a few years (>20,000 hours) in continuous operation, with improvements ongoing. Replacing stacks periodically adds to the effective TCO. Toshiba's work in Japan likely examines using unused steam segments that don't detract from power output, aiming for "stable and low-cost" hydrogen thinkgeoenergy.com – implying they believe integrating hydrogen production won't drastically raise operating costs of the geothermal plant. Additionally, because geothermal plants often have fixed operating costs (staff, field maintenance) regardless of running at full capacity or part-load, producing hydrogen during periods of low power demand can improve overall plant economics (spreading the cost over an additional revenue stream).

Cost Competitiveness: Preliminary analysis suggests that geothermal-based hydrogen can be cost-competitive with other green hydrogen, especially when high capacity factor is valued. A report by Rystad Energy noted that green hydrogen from geothermal could benefit from continuous production and potentially qualify for incentives like the U.S. hydrogen production tax credit (PTC) if emissions are low rystadenergy.com. Because geothermal hydrogen would have very low lifecycle carbon emissions (only the minimal CO₂ from drilling or construction), it could earn the full \$3/kg PTC in the USA rystadenergy.com, effectively subsidizing it heavily in early years. This could make its net cost extremely attractive.

Without subsidies, the levelized cost of hydrogen (LCOH) from geothermal at current tech is estimated in the range of \$4–6 per kg for small pilots, but with scaling, some projects aim for ~\$2/kg or lower by late 2020s. For instance, projects in Indonesia and Japan explicitly aim for cost-effective hydrogen to help decarbonize local industry thinkgeoenergy.com. If geothermal power is cheap and SOEC efficiency gains (30% less electricity use toshiba.com), there is a path to sub-\$2/kg costs, which would be quite competitive globally.

Infrastructure & Scalability Considerations: One limiting factor is that geothermal resources are geographically constrained – you can only build these systems where suitable geothermal heat exists. This means scaling up globally requires tapping many different geothermal fields rather than expanding one central facility. However, the modular nature of electrolyzers allows incremental scaling at each site.

One concern is whether diverting steam for hydrogen reduces power output: most current projects smartly utilize excess steam or off-peak capacity, but if hydrogen demand grows, some geothermal generation might be redirected from electricity to H₂ full-time. This trade-off must be managed based on market values (electricity vs hydrogen pricing). In terms of physical footprint, adding hydrogen systems to a geothermal plant is relatively small – electrolyzer units and storage tanks that can usually be sited within or near the existing power plant boundary.

From a TCO perspective, geothermal hydrogen's strengths are: no fuel cost volatility (heat is renewable and free), high utilization (capacity factor >90%) which maximizes electrolyzer use, and integrated efficiency gains. Its challenges affecting TCO include the high initial CAPEX for both drilling and SOEC, and moderate geothermal resource risk (wells can underperform, which would raise costs per kg if less steam is available than planned).

Scalability is not as straightforward as building more solar farms, but wherever good geothermal exists, replication is feasible. Places like Indonesia, Philippines, East Africa's Rift, Japan, and Western US have significant geothermal potential to host many such projects.

In conclusion, while detailed economics will vary by site, SOEC-geothermal hydrogen is projected to produce green hydrogen at competitive costs on par with other renewables-driven electrolysis, especially when operated at steady baseload (improving asset utilization) ptx-hub.org/rystadenergy.com. Near-term pilots are as

much about validating costs as technology. If they demonstrate reliable operation, the TCO is expected to drop further with mass production of SOECs and learning-by-doing.

Market Readiness, TRL, and Commercialization Prospects

The technology integration here is essentially medium maturity – the individual components have existing track records, but their combination is new. Geothermal power plants themselves are a mature technology (TRL 9, deployed for decades), and electrolysis is also a mature industrial process (though SOEC is newer, PEM/alkaline are proven). The specific combination of SOEC + Geothermal can be assigned a TRL of ~6 in 2025: it has been proven in relevant environment at pilot scale (e.g., Iceland's pilot, ongoing demos in Japan/Indonesia), but not yet widely demonstrated commercially.

Technology Readiness Level: SOEC units have been demonstrated up to multi-MW scale in industrial pilots (for example, Sunfire's 2 MW SOEC in Germany produced hydrogen successfully in 2023). So the electrolyzer technology is around TRL 7-8 on its own. Geothermal integration might introduce additional challenges like controlling steam feed quality, but these are not fundamental roadblocks. The main proof points needed are long-term operation data to ensure the geothermal steam (which may contain impurities or minerals) doesn't degrade the electrolyzer, and that the system can respond to any variability. On balance, this integration is arguably simpler than in situ hydrogen, since it's mostly above-ground equipment. The remaining development needed to declare it TRL 8-9 is mostly engineering optimization and scaling.

Current Barriers:

- **SOEC Durability and Performance:** SOEC technology, while efficient, still faces durability issues at high temperature. Degradation rates need to be minimized to make commercial projects economic (stack replacements are costly). Research to extend stack life in continuous operation (especially if using real geothermal steam which might introduce trace contaminants like H₂S or silica) is critical. Ensuring the steam fed to the SOEC is pure (perhaps requiring an extra filtration step for geothermal fluids) could be necessary, slightly complicating integration.
- **Geothermal Resource Availability:** Not every geothermal field produces the ideal conditions for electrolysis. Some have lower temperature outputs (e.g., 150 °C) which might not significantly reduce SOEC heating needs unless additional heating is provided. Very high temperature fields (supercritical geothermal) are rare. Thus, some projects might effectively use the geothermal mainly for electricity and only a bit for pre-heating, meaning the advantage over other renewables is the high capacity factor rather than a huge thermal input. This could limit the efficiency gain in some cases. Additionally, developing geothermal projects can have exploration risk and long lead times to prove the resource. This is a barrier to quick deployment compared to solar or wind which are easier to site.
- **Capital Intensity and Financing:** Upfront costs for these systems are high and investors will look for proven references. Until a few pilot-to-commercial transitions happen, financing new geothermal hydrogen projects may be challenging. The market will want to see successful continuous operation for, say, a year-long period at the Oguni or Lahendong pilot, and clear data on maintenance and costs.
- **Competing Value Streams:** Geothermal steam and power can be used for multiple purposes (electricity, direct heating, industrial processes, etc.). Using some for hydrogen is only attractive if the hydrogen's value outweighs other uses. In places with liberalized power markets, diverting power to hydrogen might lose revenue unless hydrogen demand (or incentives) is strong. Policy frameworks like clean hydrogen credits or local demand (e.g., for refining or fertilizer) will greatly influence market readiness. Without supportive policy or clear offtake agreements, developers might hesitate.
- **Infrastructure for Hydrogen Transport/Use:** Producing hydrogen at a geothermal site is one thing; getting it to market is another. Many geothermal sites are in remote areas (mountains,

volcanic zones). If local use is limited, one needs pipelines or liquefaction/trucking for the hydrogen, or conversion to carriers like ammonia or methanol (as Iceland is doing thinkgeoenergy.com). This adds complexity and requires a market ecosystem. Early projects are focusing on local use (Oguni's hydrogen is intended for nearby industrial heat demand thinkgeoenergy.com, Indonesia's may be used for refining or ammonia). Building that end-use side is part of reaching full commercialization.

Market Readiness: Despite these challenges, the prospects for commercialization are positive in regions with suitable conditions. The global drive for green hydrogen is strong, and the ability to produce it continuously (not just when the sun shines or wind blows) is a valuable niche. Geothermal hydrogen could thus command interest for providing a stable baseline supply of green H₂ or for producing green ammonia/fuels where continuous operations are preferable. We are already seeing near-commercial commitments: Iceland's projects are essentially commercial ventures (with offtake planned for methanol fuel).

In Indonesia, Pertamina's vision is to incorporate hydrogen into its geothermal business, leveraging carbon credits and future demand thinkgeoenergy.com. If the 100 kg/day pilot succeeds, scaling up to, say, 5–10 tonnes per day at a large geothermal plant would be the next step, which would be a commercial scale for industrial usage.

The technology readiness could reach TRL 8 (actual system completed and qualified) by ~2027 after these pilots, and TRL 9 (full commercial application) by 2030 in early-adopter regions. Commercialization prospects are particularly strong when coupled with hard-to-abate sectors: for instance, a geothermal hydrogen plant adjacent to a fertilizer factory (making ammonia) or steel mill (providing H₂ for DRI steel) where the continuous hydrogen supply is a benefit. As green hydrogen demand rises (driven by decarbonization goals), any region with geothermal potential will likely evaluate this option.

The U.S. DOE could also integrate geothermal hydrogen production in its hydrogen hub programs or future geothermal initiatives, further boosting readiness. In summary, SOEC geothermal hydrogen is on the cusp of demonstration to deployment – the next 2-3 years will likely see the first integrated plants operating, and with supportive economics, the approach could become a viable commercial pathway for green hydrogen in geothermal-rich markets by the end of this decade.

Key Initiatives to Advance SOEC-Geothermal Hydrogen

To accelerate market adoption and overcome current barriers, the following project initiatives are recommended:

- **Integrated Demonstration Plants (Multi-MW Scale):** Building on current pilots, develop one or more 5–10 MW SOEC-geothermal demonstration plants. For example, a project at an existing geothermal field (such as California's Salton Sea or Nevada's high-temperature fields) where a dedicated SOEC unit is added to produce on the order of 1–2 tonnes of H₂ per day. This scale would allow testing of industrial hydrogen use (such as fueling hydrogen buses or blending into natural gas pipelines for a nearby city). A DOE-backed demo in the U.S. could provide a domestic proof-of-concept to complement Iceland/Japan's efforts, and help resolve integration issues at scale (power management, thermal coupling, etc.).
- **SOEC Technology Enhancement for Geothermal Use:** Initiate an R&D program focused on material and design innovations in SOEC systems for geothermal integration. This could include developing corrosion-resistant coatings or filters to handle geothermal steam impurities, hybrid modules that can accept lower-temperature steam (150–200 °C) without performance loss, and improved stack designs for longer life. The goal would be to extend stack longevity and reduce replacement costs by, say, 50%, which directly lowers TCO. This R&D could be pursued through public-private partnerships (involving SOEC manufacturers like Toshiba, Mitsubishi or Bloom Energy along with national labs).

- **Geothermal Hydrogen Hubs and End-Use Projects:** Encourage projects that connect geothermal hydrogen production with direct end-use to create a complete value chain. For instance, a “Geothermal Hydrogen Hub” could be established – similar to DOE’s regional hydrogen hubs – in a place like the Salton Sea Known Geothermal Area or Indonesia’s Java geothermal cluster. Such a hub would include hydrogen production, storage, and consumption (e.g., a hydrogen-fired power plant or ammonia production on-site). One specific initiative could be in Kenya’s Olkaria geothermal park, where a pilot plant produces hydrogen that is then synthesized into green fertilizer. This not only advances the production technology but also demonstrates the market application, addressing the infrastructure barrier by consuming hydrogen on-site.
- **Policy and Market Development:** On the non-technical side, governments should integrate geothermal hydrogen into clean energy strategies. This could mean targeted incentives or feed-in tariffs for hydrogen produced from geothermal power, or inclusion in hydrogen procurement mandates. A project activity here would be a policy demonstration – for example, a local municipality or military base commits to buying a certain amount of geothermal-produced hydrogen for its fuel cell vehicles or backup generators. This kind of initiative, paired with a pilot plant, can provide guaranteed offtake and financial viability to early projects, proving the business case.
- **International Knowledge-Sharing Consortium:** Because geothermal resources and expertise are globally distributed, forming a consortium (perhaps under the IEA or the International Geothermal Association) to share data from these pilots is invaluable. A formal initiative to pool lessons learned – from Oguni, Lahendong, Hellisheiði, etc. – will accelerate learning. This can be done via an international working group or a series of “Geothermal Hydrogen Demonstration” testbeds in different countries, coordinating through DOE and counterparts abroad. By comparing notes, the time to commercialization can shrink and best practices for design and operation will emerge more quickly.

Natural (Geologic) Hydrogen

Technology Basics and Underlying Principles

Natural hydrogen, sometimes referred to as “white hydrogen,” is molecular hydrogen that is generated by geologic processes in the Earth’s crust and can accumulate in subsurface reservoirs, much like natural gas. Unlike in situ hydrogen (which involves human-initiated reactions underground), natural hydrogen is produced continuously by natural reactions without human intervention. The key underlying processes include [ry.stadenergy.com](https://www.rystadenergy.com/):

- **Serpentinization:** a chemical reaction between water and iron-rich minerals (typically in ultramafic rocks like peridotites in the mantle or deep crust). When water infiltrates these rocks at elevated temperature, iron (Fe^{2+}) gets oxidized, and H_2 is released. This is well-known at mid-ocean ridges and ophiolite belts on land. Serpentinization is considered a primary source of natural H_2 on Earth [ry.6](#). It can produce a steady stream of hydrogen gas as long as reactable minerals and water are present.
- **Radiolysis of Water:** radioactive decay of elements like uranium, thorium, and potassium in rocks generates radiation that can split water molecules in situ, yielding hydrogen (and oxidants). In ancient shield areas or granitic rocks with natural radioactivity, this process can slowly accumulate hydrogen over geologic time [rystadenergy.com](https://www.rystadenergy.com/).
- **Water-rock reactions with reduced minerals:** beyond serpentinization, other reactions such as the oxidation of siderite, magnetite, or sulfide minerals by water can produce H_2 . Also, interaction of water with natural hydrocarbons or graphite in rock under certain conditions can generate hydrogen.
- **Biological generation:** in some cases, subsurface microbes (especially certain archaea or bacteria) can generate hydrogen as a byproduct of their metabolism of organic matter. However, most subsurface biology tends to *consume* hydrogen (as an energy source) rather than produce it, so biological generation is likely minor in pure natural hydrogen accumulations.

Hydrogen produced by these processes can migrate and accumulate in subsurface traps similar to conventional gas fields if a caprock is present to prevent it from escaping to the surface. Historically, it was believed that hydrogen, being a small, light molecule, would not remain trapped for long and would quickly diffuse away or be consumed by microbes. However, recent discoveries have challenged that assumption [erin.eurystadenergy.com](https://www.erin.eurystadenergy.com/). For instance, in certain geologic settings, hydrogen gas has been found seeping at the surface or collected in wells at surprisingly high concentrations, indicating a subsurface source feeding an accumulation.

One emblematic case is the discovery of hydrogen in Bourakebougou, Mali. In the 1980s, a borehole drilled for water encountered a gas that was later found to be rich in hydrogen (up to ~98% H_2) [nature.com](https://www.nature.com/). Over the years, additional wells confirmed the presence of a natural hydrogen reservoir, apparently continually replenished by the geology (possibly related to an underlying Proterozoic craton with uranium-rich rocks and water – radiolysis being a suspected source). This Mali discovery proved that pockets of nearly pure hydrogen can exist underground on a timescale useful for human exploitation e360.yale.edu.

Natural hydrogen is dubbed *white* or *gold hydrogen* to signify its carbon-free origin (and in the case of “gold,” the potential value as a clean energy resource). The principle of extracting it is straightforward: drilling into a known or suspected hydrogen-rich reservoir, much as one would drill for natural gas. The raw gas from the well might contain hydrogen mixed with other gases (nitrogen is common, also methane or helium in some cases). If hydrogen content is high (say >50%), the gas could potentially be used directly in fuel applications or separated. Crucially, natural hydrogen extraction does not involve a production step generating emissions – it is akin to mining a naturally occurring clean fuel.

To find natural hydrogen, geoscientists look for indicators such as H₂ surface seeps, soil gas anomalies, certain rock types (e.g., ultramafic rocks, banded iron formations, or suture zones) and even unexplained subsurface pressure anomalies. There is also interest in using new hydrogen-specific sensors and geophysical methods to identify reservoirs rystadenergy.com. For example, hydrogen-sensing probes that can detect dissolved H₂ in groundwater in boreholes up to 1500m deep are now being used rystadenergy.com. These tools, along with remote sensing for serpentinized rocks or micro-seismic signals from hydrogen gas migration, are part of the exploration toolkit being developed.

In summary, natural hydrogen technology is about exploration and extraction: find where Earth itself produces hydrogen and accumulate it, and develop those occurrences as one would a conventional gas field. Underlying it are natural geochemical reactions (serpentinization, radiolysis, etc.) that act as an on-going “geologic electrolyzer,” albeit at a much slower rate than industrial processes. The allure is that if sizable reservoirs are found, humanity could tap a *renewable geological source* of hydrogen that requires no energy input or CO₂ output – a potential “gamechanger for the clean hydrogen sector” rystadenergy.com. It moves hydrogen from just an energy carrier we must produce into a primary energy source that can be harvested rystadenergy.com, akin to drilling for geothermal heat or natural gas.

Current Level of Activity (Exploration, Discoveries, Research)

Until recently, natural hydrogen was not systematically sought, and most finds were accidental. Now there is rapidly growing activity on multiple fronts – commercial exploration, academic research, and governmental resource assessments:

- **Known Discoveries and Pilot Extraction:** The Mali hydrogen field at Bourakebougou remains the only site with *ongoing utilization* of natural hydrogen so far. The company Hydroma (formerly Petroma) has run a pilot there for years, using the hydrogen gas to generate electricity for the local village elijah-geo.com. It produces on the order of 5 tonnes of hydrogen per year (roughly 0.5 kg/hour) e360.yale.edu rystadenergy.com, a small but continuous output. This pilot plant demonstrates that hydrogen can be extracted and used directly (in this case, via a genset to produce power) and that the reservoir recharges – presumably from natural processes – as the gas is produced errin.eu.

Aside from Mali, there are reported high-concentration hydrogen seeps in other places: Brazil (recurring reports of >15% H₂ in wells in São Paulo state), Russia (Yakutia region, natural gas with 10-20% H₂), USA (Kansas, where gas from old exploration wells contained a few percent hydrogen, spurring new interest) fuelcellworks.com. In 2023, a French company (45-8 Energy's offshoot, Mantle8) reported detecting up to 2,500 ppm H₂ (~0.25%) in the Pyrenees during a field survey, confirming predictive models for hydrogen presence nath2investing.com. While 0.25% is low, the context matters: it suggests an active hydrogen system that could be richer in concentrated traps nearby. Similarly, in South Australia, historical data from the 1920s (Ramsay Oil Bore) indicated high hydrogen (80%+) in a borehole. This lay largely dormant in the literature until recently, when companies re-analyzed it.

- **Commercial Exploration Companies:** A wave of startups and juniors has formed to explore for natural H₂, particularly since 2020. For example, **Gold Hydrogen Ltd.** in Australia acquired the exploration license over the Ramsay field and in late 2023 drilled new test wells, reportedly confirming hydrogen concentrations up to ~86% H₂ in the subsurface gas rystadenergy.com. They plan further drilling in 2024 and a pilot feasibility study thereafter rystadenergy.com.

In the USA, **Natural Hydrogen Energy LLC** drilled an exploration well in Nebraska in 2019 (the Hoarty well) to test a basement structure for hydrogen; while detailed results weren't published, it helped refine exploration methods. Another U.S. company, **Fuelcell Energy (Trillium)**, is looking at hydrogen in Kansas and has claimed some success in detecting reservoirs. In Europe, companies like **45-8 Energy (France)** and **Helios Energy (Spain)** are actively sampling wells and planning exploration drilling in geological settings like the Lorraine Basin and Spanish Pyrenees, respectively. In 2022, **Engie** (a major French energy firm) also invested in evaluating natural hydrogen plays, signaling serious interest.

- **Government and Academic Research:** Governments are acknowledging natural hydrogen's potential. The European Commission put out a 2023 call to map and assess Europe's natural hydrogen resources [errin.euerrin.eu](https://ec.europa.eu/energy/en/news/european-commission-launches-call-map-assess-natural-hydrogen-resources). The expected outcomes include methods to identify prospective areas and understanding regulatory barriers [errin.euerrin.eu](https://ec.europa.eu/energy/en/news/european-commission-launches-call-map-assess-natural-hydrogen-resources). The International Energy Agency's Hydrogen TCP launched **Task 49: Natural Hydrogen** to promote experience exchange and assess legal frameworks [ieahydrogen.org](https://www.ieahydrogen.org/). The U.S. Geological Survey (USGS) has initiated studies to evaluate hydrogen occurrences in the U.S., and the state of South Australia in 2021 officially added hydrogen to its list of regulated resources (which spurred a rush of license applications) [rystadenergy.com](https://www.rystadenergy.com).

Academic interest has exploded, with conferences and special journal issues dedicated to "natural hydrogen exploration." Geologists are revisiting old well records and geochemical data to identify missed H₂ shows. Notably, researchers are studying "**Fairy Circles**"—peculiar depressions in soil in various countries—that have been found to coincide with slow hydrogen seeps that kill vegetation, possibly indicating subsurface accumulations. Such clues are now being systematically investigated with modern instruments.

- **Recent Noteworthy Developments:** In addition to the above, a 2022 *WIRED* article and others brought wider attention to natural hydrogen (sometimes blending it conceptually with "gold hydrogen" microbial ideas) [wired.com/wired.com](https://www.wired.com/wired.com). In mid-2023, Rystad Energy published an analysis calling natural H₂ the new "white gold rush," highlighting that dozens of companies globally are now on the hunt and that the resource, if found in quantity, could meet a meaningful portion of hydrogen demand by 2030 [thehydrogenpodcast.com rystadenergy.com](https://www.thehydrogenpodcast.com/rystadenergy.com). Exploration techniques are evolving: besides direct detection, some are leveraging analogies to helium exploration (since helium and hydrogen often co-occur as they are both light gases from basement rock).

It's important to note that as of 2025, no large-scale commercial production of natural hydrogen exists yet – only pilot-scale and exploration. But the level of activity is high and accelerating: over 20 companies worldwide are engaged in natural hydrogen exploration, at least half a dozen test wells are planned in the next 1-2 years, and governments are funding R&D to quantify this resource. In many ways, this mirrors the early days of the oil industry (circa late 19th century) when seeps and wildcat wells guided the first discoveries – we are in the exploratory "gold rush" phase for H₂.

TCO (Total Cost) and Scalability Considerations

If substantial natural hydrogen reserves are confirmed, the economics of extracting this hydrogen could be extremely attractive. Unlike manufactured hydrogen, where feedstock and energy drive cost, natural hydrogen would be akin to a mining operation with upfront exploration and well development costs, but low operating costs. Key considerations:

- **Exploration and Drilling Costs:** The initial costs (analogous to upstream oil & gas) involve geological surveys, seismic studies, and drilling wildcat wells to find hydrogen. These costs can be high and are sunk costs that must be amortized over any successful finds. However, exploration for hydrogen might be cheaper than for oil in some respects – hydrogen tends to occur at shallower depths in some cases (the Mali wells are only a few hundred meters deep [nature.com](https://www.nature.com)). Also, some prospecting can leverage existing data from oil/gas wells (looking at gas composition logs for hydrogen traces). That said, early explorers will need risk capital, as not every prospect will have a commercial accumulation. Government support in this phase (through tax incentives or geological surveys) can mitigate these costs.
- **Development and Production Costs:** Once a hydrogen-bearing structure is found, developing it would involve drilling production wells and potentially installing surface facilities to separate and handle the gas. Fortunately, hydrogen in these contexts is often found with inert gases like nitrogen, which require minimal processing. If the gas is very pure hydrogen, it could be dried and compressed directly. If mixed with some methane or helium, separation units might be needed –

for instance, membranes or pressure swing adsorption to get high-purity H₂ for certain uses. These add to CAPEX/OPEX but are standard technologies. Importantly, no reformers, gasifiers, or electrolyzers are needed – the Earth has done the work. This eliminates the largest cost component present in other hydrogen pathways.

- **Operating Costs:** These would mainly be the costs of running the wells (power for compressors to bring gas to surface if needed, maintenance of valves and pipes) and possibly compression for transport. If hydrogen is simply flared (burned) – which it wouldn't be for production, but just to test flows – it shows that the resource itself is free. For actual use, one might compress hydrogen to 350 bar for trucking or pipeline injection, which takes energy (roughly 5–10% of the hydrogen's energy content). However, relative to producing hydrogen via electrolysis or SMR, the operating energy use is minimal.
- **Cost Estimates:** Rystad Energy estimates that white hydrogen could be produced for ~\$1 per kg or less at scale rystadenergy.com. In Mali, Hydroma's pilot has an estimated production cost as low as \$0.50 per kg H₂ rystadenergy.com – largely the cost of running the generator and well maintenance. In Spain and Australia, companies are indeed targeting around \$1/kg for future projects rystadenergy.com. These figures are dramatically lower than green hydrogen from electrolysis (often \$4–6/kg today) or blue hydrogen from SMR+CCS (~\$2/kg). The reason is simple: nature's providing the hydrogen and the "separation" from energy sources has already occurred underground with no human-paid energy. The remaining costs are similar to producing natural gas, which is cheap on an energy basis.
- **Scalability:** If natural hydrogen exists in large accumulations, scalability would depend on how many such fields can be found and developed. This is akin to oil/gas – it scales by exploration success and drilling more wells. One difference is the renewability: some estimates suggest certain geologic systems could continuously replenish hydrogen over time (serpentinization can run for millions of years). This hints at a potentially sustainable extraction rate – one could produce a certain amount per year without depleting the resource quickly, if the replenishment is comparable to extraction. However, if extraction far outpaces generation, the field would eventually decline (like a normal gas field). The scalability is thus tied to geological renewal rates or sheer number of fields.

The Earth's capacity to generate hydrogen is not yet known. Optimistic projections (e.g., by some experts like Dr. Alain Prinzhofer) suggest it could be huge, but rigorous numbers await exploration results. From a cost perspective, scaling up production means drilling more wells – which in established oil/gas practice can be done relatively quickly and in parallel across different regions. There is no fundamental supply chain bottleneck as with manufacturing electrolyzers or building large chemical plants. In that sense, if hydrogen fields are abundant, scaling extraction could be faster than scaling green hydrogen production infrastructure. The challenge will be finding them and confirming sizes.

- **Infrastructure and Market:** Natural hydrogen, once at surface, faces the same transport/storage issues as any hydrogen. If produced in remote areas (deserts, outback, etc.), infrastructure to get it to market is needed. This could be pipelines dedicated to H₂ (which involves materials that can handle hydrogen's embrittlement effect, etc.), conversion to ammonia for shipping, or local usage (e.g., power generation on-site and sending electricity out, though that loses some energy advantage). The cost of building this midstream infrastructure can be substantial and must be included in any TCO for delivered hydrogen. One mitigating factor: if a hydrogen field is near existing natural gas pipelines, blending is an option (some countries allow up to 5-15% H₂ blending in gas grids currently). Or, if helium is present (a valuable byproduct, as some hydrogen-prone geology might also contain helium), selling helium could offset costs.

In summary, the TCO of natural hydrogen extraction could be extremely low on the production end – literally the cost of drilling and operating wells, which for large gas operations can be <\$1/GJ (which is <\$0.12/kg H₂ equivalent!). Realistically, including exploration amortization and transport, the delivered

cost might be a few dollars per kg. Even so, this would undercut most other forms of hydrogen. Natural hydrogen thus has the potential to be the least expensive source of hydrogen if sizable reserves are confirmed rystadenergy.com. The combination of ultra-low cost and zero-carbon footprint (aside from incidental emissions) is precisely why it's drawing attention.

The main caveat: it's only scalable if the Earth provides enough of it in accessible accumulations, which is still an open question. In terms of lifecycle emissions, natural hydrogen production is very clean – Rystad calculates that even if some methane is co-produced, the carbon intensity can be as low as 0.4 kg CO₂e per kg H₂ (at 85% H₂ purity) rystadenergy.com. This easily meets the strictest low-carbon criteria (like the US IRA's 0.45 kgCO₂e/kg for full credit) rystadenergy.com. Thus, natural hydrogen could qualify for premium incentives, further improving its economic proposition if those policies are in play.

Market Readiness, TRL, and Commercialization Prospects

TRL Assessment: Natural hydrogen exploration is currently around **TRL 3-4** (analytical and experimental proof-of-concept). We have proof that the phenomenon exists (Mali, etc.), but we do not yet have a proven method to reliably find and commercially extract it at scale. The Mali pilot can be seen as a TRL 5 demonstration in an operational environment, albeit small ellis-geo.com. The next exploration wells being drilled in 2023-2025 will likely elevate the TRL as discoveries are made and pilot production tests are conducted. To reach TRL 7+ (system prototype in operational environment), a larger pilot (say producing tens of kg of H₂ per hour over months) is needed; this could happen in the next couple of years if companies like Gold Hydrogen or others strike a good reservoir.

Barriers and Challenges:

- **Geological Uncertainty:** The biggest barrier is simply the unknown nature of the resource. We do not yet understand how common or rare large hydrogen accumulations are. It's possible that most hydrogen seeps do not lead to big traps – the gas might be generated diffusely and lost. Until exploration drills significant prospects, there is high uncertainty. This makes investors cautious. Overcoming this barrier requires accumulating more empirical data (which is happening now).
- **Regulatory Framework:** Many countries have no legal classification for hydrogen extracted from the ground. For example, is it a mineral, a gas, or something else? In some jurisdictions, rights to it might default to the state or to whoever has hydrocarbon rights. Clarifying this is essential for companies to have security. South Australia was proactive in 2021 by amending regulations to include hydrogen rystadenergy.com, enabling exploration licensing. Others will need to follow. The IEA H₂ Task 49 is looking at these frameworks ieahydrogen.org. If regulations lag, that could slow projects.
- **Technical – Drilling and Containment:** Hydrogen is a small molecule and can escape through materials that trap hydrocarbons. There's concern that even if a trap exists, hydrogen might slowly leak or diffuse through caprocks that are leaktight for larger molecules. This implies careful analysis of caprock mineralogy is needed (e.g., hydrogen can react with certain minerals or be absorbed). Also, well materials: hydrogen can embrittle steel, so production wells might need specialized steel or liners. However, since many wells handle hydrogen sulfide (H₂S) which also can cause embrittlement, the industry has some experience in mitigating that (e.g., using Chrome steels). Surface facilities must consider hydrogen's flammability – though similar to natural gas handling, H₂ has different properties (wider flammable range, lower ignition energy). These technical issues are manageable but require establishing best practices.
- **Microbial Consumption:** A curious challenge is that subsurface microbes, if present in the reservoirs, might consume hydrogen (to produce methane, for example, via methanogenesis). Some natural hydrogen systems might actually get “poisoned” by microbial activity over time (turning the H₂ into CH₄). In fact, one theory is that this is why we often find hydrogen accompanied by some methane in seeps – microbes were at work. Thus, sustaining a reservoir

might involve ensuring certain conditions (temperature, sterility) that limit microbial uptake. This is a research question being examined in natural hydrogen studies errin.eu.

- **Market Skepticism:** Because the concept sounds almost too good to be true (clean hydrogen out of the ground), some stakeholders are skeptical. Overcoming this will require demonstrable successes. The first company to sell say 99.999% pure hydrogen cylinders sourced from a natural well will make a splash and begin changing minds. Until then, conservative energy players may watch from the sidelines.

Commercialization Prospects: If even a handful of moderate-sized natural hydrogen fields are found (for instance, equivalent to a modest natural gas field in energy content), the route to commercialization could be fast. The reason is the extraction technology leverages the century-old oil & gas industry skillset. Existing drilling contractors, service companies, and even infrastructure could pivot to hydrogen with minor tweaks. As Rystad noted, white hydrogen could capture a notable share of the hydrogen market by 2030 if exploration succeeds thehydrogenpodcast.com.

For example, McKinsey projected it might supply 10% of the global H₂ market by 2030 in a high scenario thehydrogenpodcast.com. This suggests a timeline where by the late 2020s, we might see the first commercial natural hydrogen production (beyond Mali's pilot). Companies in Australia plan pilots by 2025 and potential commercialization by 2027-2028. In the US, if Kansas/Nebraska prospects pan out, those could also be on a similar timeline given the IRA incentives align well with white H₂ production rystadenergy.com.

Market readiness today is low – no established supply chain or marketplace for geological hydrogen exists. But it can piggyback on the natural gas infrastructure. For instance, hydrogen could be blended into existing gas pipelines if a field is near one, effectively providing a clean supplement to natural gas. Alternatively, if purity is high, it could feed local fuel cell projects or be trucked to industrial users. The first commercialization will likely be small-scale: supplying a local industrial park or fuel station, gradually ramping up. Over time, if large volumes are proven, dedicated hydrogen pipelines or conversion to ammonia for export might come into play (particularly in places like Australia aiming to export energy).

A key point: natural hydrogen directly supports the DOE Hydrogen Shot goals by potentially delivering \$1/kg hydrogen without massive new infrastructure. It shifts the narrative from building electrolysis everywhere to also finding hydrogen. The commercialization will therefore also depend on how it fits into hydrogen economy plans – but since it is “green” (zero-carbon) by definition, it should enjoy policy support in frameworks aiming for clean H₂.

In conclusion, natural hydrogen is not yet market-ready – it's in the resource discovery phase – but it has a plausible path to rapid adoption if significant resources are verified. The next 5 years are critical: they will reveal whether natural H₂ is a niche curiosity or a major new energy resource. If the latter, expect a scramble akin to new oil rushes, but this time for a clean fuel. By the early 2030s, we could see natural hydrogen contributing to hydrogen supply in multiple countries, with Mali's project scaled up and new ones online, thereby transitioning this from a scientific oddity to a commercial reality.

Key Initiatives to Advance Natural Hydrogen Exploration and Production

Several initiatives would substantially advance the understanding and development of natural hydrogen as a resource:

- **Geological Survey and Exploration Drilling Programs:** A coordinated effort to perform geophysical surveys (seismic, magnetotelluric, remote sensing) and exploratory drilling in key prospective regions. This could be spearheaded by government geological agencies (e.g., USGS, Geoscience Australia, BRGM in France) in partnership with industry. For example, a Natural Hydrogen Exploration Program that funds a dozen wildcat wells in various basins worldwide (selected based on promising geology such as cratonic shields, ophiolites, or historical anomalies) would greatly accelerate discoveries. Each well would be logged with modern gas

detection tools to identify hydrogen-bearing zones errin.euerrin.eu. The data from these would help confirm play concepts and encourage private investment by reducing geological risk.

- **Advanced Detection and Monitoring Technology Deployment:** To support exploration, specialized tools need to be field-tested and deployed. Initiatives here include installing hydrogen sensing networks in areas of interest (analogous to how methane seeps are surveyed). For instance, deploying deep hydrogen probes in existing boreholes (perhaps in mining exploration holes or abandoned wells) to map hydrogen at depth rystadenergy.com. Another project could develop and launch a satellite or aerial survey specifically tuned to detect subtle hydrogen-induced alterations on the surface or in vegetation (similar to mineral exploration techniques). Additionally, pilot projects using real-time drilling gas analyzers optimized for H₂ could be run, so that as an exploration well is drilled, hydrogen shows are immediately identified and quantified, improving decision-making on well depths and testing.
- **Pilot Production and Utilization Project:** Once a natural hydrogen occurrence is confirmed, an important next step is a pilot production facility to demonstrate sustained extraction and use. An initiative could be to scale up the Mali operation or a new discovery to a continuous production of, say, 50–100 kg of H₂ per day, and use this hydrogen in a real application. For example, a “Hydrogen from the Earth” pilot project could involve powering a fleet of fuel cell vehicles in a nearby city or blending into a local power plant. This would test production logistics (purification, compression, storage) and provide a case study in end-to-end natural hydrogen utilization. It would also help address any regulatory and safety issues in handling the gas. Such a project, under public-private sponsorship, would pave the way for commercial field development.
- **Enhancing Natural Hydrogen Generation (Stimulation):** Research-oriented initiatives might explore whether we can *assist nature* in producing more hydrogen in situ. One idea is enhanced serpentinization – e.g., injecting water or catalysts into suitable rock formations to boost the H₂ generation rate rystadenergy.com. A pilot experiment in a deep mine or dedicated borehole could be conducted to see if magnetite or other catalysts can significantly increase hydrogen output from a known reaction zone. Similarly, trials of heating certain rock strata (via geothermal probes) to simulate the conditions for hydrogen production could be insightful. While not necessary for finding natural H₂, these approaches could one day turn subcommercial seepages into productive wells and are worth investigating now.
- **Regulatory and Knowledge Framework:** Establish a **Natural Hydrogen Knowledge Center** (virtual or physical) where all findings, best practices, and data are aggregated and shared (to the extent possible given proprietary data). This initiative would include drafting template regulatory guidelines – for example, model contracts or licensing terms for natural hydrogen exploration, environmental guidelines for venting/testing (hydrogen has different considerations than methane), and safety standards for drilling (hydrogen’s flammability means sensors and blowout preventers need to account for it). Having a clear framework can significantly advance readiness by removing legal uncertainties and ensuring safe operations as soon as discoveries are made errin.euerrin.eu.

By pursuing these initiatives, stakeholders can shorten the timeline from random discovery to systematic development of natural hydrogen. Together, they address the exploration risk, technology needs, practical demonstration, and governance – the combination of which will be key to turning natural hydrogen into a viable component of the clean energy portfolio.

Addendum

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