INDONESIAN JOURNAL ON GEOSCIENCE
Geological Agency
Ministry of Energy and Mineral Resources

Journal homepage: https://ijog.geologi.esdm.go.id
ISSN 2355-9314, e-ISSN 2355-9306

Analytical Review of Natural Hydrogen Sources and Occurrence for Sustainable Hydrogen Future in Indonesia

Andi Mardianza[1], Cindy Dianita[2], and Adi Widyantoro[1]

[1]PT Pertamina Hulu Energi, Jakarta, Indonesia
[2]Department of Chemical Engineering, Faculty of Engineering, Universitas Indonesia, Depok, West Java 16424

Corresponding author: cindydianita@ui.ac.id
Manuscript received: September 02, 2025; revised: April 05, 2025;
approved: June 02, 2026; available online: October 20, 2026

Abstract - One transformative, inexpensive (~$0.5-1/kg), and low-carbon energy source is natural hydrogen produced by serpentinization and other geochemical processes. Global data on its accumulation, migration, and geological mechanisms have been collected in the present study. Temperature, pressure, and mineralogy all affect the rate at which hydrogen is generated. While very limited hydrogen is produced at low temperatures (0.01-1 mmol/kg), significant production (1-100 mmol/kg) is made possible by ideal hydrothermal conditions (200-315° C), with extremely high rates (100-360 mmol/kg) possible under extreme experimental conditions. The evaluation of Indonesia's enormous potential, situated within the vast East Sulawesi Ophiolite Belt, is a primary focus. The country's tectonic environment offers the three necessary components for a significant hydrogen play: a steady geochemical engine, a large supply of source rock, and efficient migration routes. Consequently, Indonesia stands poised to emerge as a potential leader in the regional hydrogen economy. To realize this potential, specific exploration and regulatory support must be initiated, and technical issues related to gas purity must be resolved. This work presents the scientific and financial justification for prioritising natural hydrogen in the global energy transition.

Keywords: natural hydrogen, serpentinization, hydrogen exploration, energy transition

© IJOG - 2026

How to cite this article:
Mardianza, A., Dianita, C., and Widyantoro, A., 2026. Analytical Review of Natural Hydrogen Sources and Occurrence for Sustainable Hydrogen Future in Indonesia. *Indonesian Journal on Geoscience*, 13 (3), p.455-472. DOI:-0.17014/ ijog.13.3.455-472

Introduction

In alignment with the 2020 Paris Agreement, nations worldwide have committed to reducing atmospheric carbon emissions to mitigate rising global surface temperatures (Times of India, 2025), while natural hydrogen is increasingly viewed as a potential contributor to achieving a net-zero carbon future, prompting growing interest in its scientific foundations, economic viability, and ongoing global exploration efforts (Singh, 2025).

Beyond the established categories of green and blue hydrogen, a promising alternative has emerged, also referred to as natural hydrogen. This form of hydrogen is generated through geochemical processes within the earth's subsurface, such as serpentinization, radiolysis, and the oxidation of iron-rich minerals (CSIRO, 2024). Natural hydrogen offers significant economic advantages, with production costs estimated between USD 0.5 and 1 per kilogram, making it the most cost-effective hydrogen source currently identified (Rystad Energy, 2024). In comparison, green

PUBLISHED IN IJOG

hydrogen production costs range from USD 3 to 8 per kilogram, while blue hydrogen costs between USD 1 and 2 per kilogram (International Energy Agency/IEA, 2021).

In addition to its economic benefits, natural hydrogen production is environmentally advantageous. Studies suggest that its greenhouse gas emissions can be as low as one-third of those associated with green hydrogen, positioning it as a low-emission energy source (Zgonnik, 2020). These attributes, cost-effectiveness and low carbon intensity, highlight the potential of natural hydrogen as a sustainable and economically viable energy solution for the global transition toward clean energy.

Methods

This paper is mainly based on an analytical review of previous studies and global case data on natural hydrogen. In some cases, the description of geochemical formation processes, documentation of occurrences in various geological settings, and economic viability analysis have been attempted. These efforts aim to establish a comprehensive understanding of natural hydrogen generation mechanisms, to correlate its potential occurrences with relevant geological settings, and to determine its viability as an alternative to synthetic hydrogen. This review provides additional information and underscores the need to explore this resource in Indonesia.

Natural Hydrogen Occurrences and Migration

Natural hydrogen in the shallow subsurface exists in several forms, including as free gas in surface seeps, dissolved in groundwater, and trapped within fluid inclusions in rock formations. Its migration occurs through various processes such as molecular diffusion and fluid-driven advection (Farver, 2010; Zgonnik, 2020). The movement of hydrogen from underground reservoirs to the surface, and eventually into the atmosphere, is influenced by multiple factors, including the source of the hydrogen, the mode of transport, and the characteristics of the geological media it passes through. As a result, there remain significant gaps in scientific understanding regarding how natural hydrogen behaves below the Earth's surface.

Hydrogen Diffusivity in Crystalline And Sedimentary Rocks

Several key factors, including mineral composition, rock texture, and surrounding environmental conditions, influence the migration of hydrogen through crystalline rocks. In fine-grained volcanic materials such as natural glasses, hydrogen diffusion can occur at extremely fast rates. This rapid diffusion has significant implications for hydrogen degassing processes, particularly in hydrothermal systems and submarine environments where hydrogen may be released from deeper mantle sources. In contrast, coarser crystalline rocks like granite, especially those found in ancient continental interiors, tend to preserve hydrogen over extended geological periods. These rocks often contain textural features that allow hydrogen to be stored within fluid inclusions, maintaining elevated concentrations over billions of years (Bourdet *et al.*, 2023; Hutchinson *et al*., 2024). As a result, these granitic terrains represent an important reservoir of hydrogen in continental geological settings.

Hydrogen diffusivity in sedimentary rocks is strongly influenced by environmental variables such as temperature, pressure, and salinity. When temperature increases, the ability of hydrogen to migrate through the rock typically becomes greater. However, increases in pressure and salinity can substantially hinder this movement, in some cases reducing the diffusivity by several magnitudes (Hoskin and Sundeen, 1985; Demouchy, 2010; Li and Chou, 2015; Speciale *et al*., 2020; Liu *et al.*, 2022). These environmental factors play a crucial role in determining whether a rock formation facilitates or restricts hydrogen movement. Their influence is especially important when evaluating sedimentary basins for hydrogen resource development or underground storage potential, as they control not only the speed but

PUBLISHED IN IJOG

also the spatial extent of hydrogen transport across different geological layers.

In most sedimentary rocks, the time required for hydrogen to traverse a single meter is typically measured in years. This duration becomes even longer in formations with low permeability, such as salt deposits or dense clays, where hydrogen moves much more slowly (Bagreev *et al.*, 2004; Vinsot *et al.*, 2014; Keshavarz *et al.*, 2022). Variability in temperature and the chemical composition of groundwater throughout the year introduces additional complexity to the system. For instance, after intense rainfall, fresh water may infiltrate saline aquifers, reduce salinity, and enable these formations to shift from acting as hydrogen barriers to becoming migration pathways. On the other hand, drying conditions can reverse this effect. Laboratory experiments support these observations, showing that breakthrough times for hydrogen vary substantially depending on the amount of water present in the rock. This variation is particularly evident in rocks with tiny pore spaces, where moisture content can significantly accelerate or delay hydrogen transport (Strauch *et al.*, 2023). Understanding these dynamic interactions is essential for predicting how natural hydrogen behaves in both shallow and deep geological environments.

Faults and Fractures

There are several documented examples of natural hydrogen seeps that demonstrate steady and continuous release of hydrogen to the Earth's surface over thousands of years. These seeps have been observed in locations where deep geological faults intersect rocks that are rich in hydrogen-producing minerals, such as serpentinized crystalline basement rocks (Hosgörmez, 2007). In addition to these consistent emissions, there are also cases of episodic hydrogen releases that have been linked to tectonic activity. These periodic pulses are often associated with processes such as the movement of groundwater triggered by seismic activity, the effects of recent fault movements, and the migration of carbon dioxide within the subsurface (Firstov and Shirokov, 2005). In tectonically active areas, the relationship between rock stress, fault permeability, and fluid flow is dynamic. Fault systems in such regions are continually evolving, and changes in their structure can either enhance or restrict the movement of hydrogen through the crust.

On a larger spatial scale, the dominant mechanism for hydrogen movement is fluid-driven advection through fault zones that cut across thick layers of the Earth's crust. Hydrogen-rich fluids are capable of migrating long distances along these structural pathways, leading to natural surface emissions that have been observed and recorded in multiple parts of the world. Notable case studies include hydrogen seeps documented in Mali, Brazil, and the northern Pyrenees, where geologic investigations have linked these phenomena to fault-controlled transport systems (Prinzhofer *et al.*, 2018). Faults and fractures serve as efficient channels for hydrogen migration over both short and extended timeframes. They allow gases to move upward from deep sources toward the surface, facilitating their escape into the atmosphere. These findings highlight the crucial role of large-scale structural geology in enabling the transport and release of natural hydrogen from deep within the earth crust.

Understanding and Modelling Subsurface Hydrogen Migration

Subsurface hydrogen migration is governed by a series of interconnected physical and chemical processes that are often difficult to distinguish. The concept of causal pathways, sequences of cause-and-effect relationships, can be used to unravel these interactions. Causal inference methods, as described by Pearl (2009), allow researchers to assess the independent effect of variables in complex systems. This is particularly important in subsurface environments, where surface flux measurements may reflect a combination of biological activity, geochemical reactions, and fluid dynamics. For example, microbial hydrogen consumption can produce short-term fluctuations, while deeper and slower geological processes such as serpentinization or changes in salinity

PUBLISHED IN IJOG

and pH drive long-term hydrogen supply (Runge *et al.*, 2019).

To accurately assess these causal mechanisms, observational data must often be decomposed using physical constraints and statistical regularization. This can include the definition of relevant variables, specification of functional relationships, identification of noise distributions, and consideration of time delays and aggregation in the data (Runge *et al*., 2019). These methods become especially valuable when integrated with computational fluid dynamics (CFD) simulations, allowing modelers to remove irrelevant or redundant variables. Focusing solely on the dominant physical drivers significantly reduces the computational burden of large-scale simulations without compromising accuracy.

The natural movement of hydrogen through geological formations is influenced by both long-term and transient processes. In stable, deep crystalline rocks such as Archean or Proterozoic Cratons, hydrogen production via water radiolysis may continue over millions of years. However, in the overlying sedimentary basins, migration pathways are often controlled by localized factors. These include microbial interactions in soil, fluid advection along fault zones, and temporary entrapment in fine-grained layers such as shales or evaporites. Environmental variability plays a key role in modulating system behaviour. For instance, a saline aquifer may initially act as a barrier to hydrogen flow but can become a transport medium when diluted by meteoric water during periods of high rainfall.

The migration of hydrogen within porous geological media occurs through three primary mechanisms: advection in the gas phase, advection in solution, and molecular diffusion. Each mode becomes dominant under specific pressure and temperature conditions, typically when solubility thresholds are exceeded. According to Hutchinson *et al.* (2024), pore throat diameter exerts a major control on the migration mechanism. In formations with larger pores, such as sandstones, advective transport dominates, whereas in tighter formations like shales or evaporites, diffusion becomes the prevailing process. Capillary entry pressure can also inhibit gas-phase flow, halting Darcy-type advection until buoyancy forces exceed this threshold.

Incorporating these complex dynamics into reservoir-scale models presents significant technical challenges. High-resolution models with numerous grid blocks are computationally expensive due to the volume of equations that must be solved simultaneously.

Natural Hydrogen Potential

Natural Hydrogen Hotspots

As an upper-bound estimate, it can be considered that, on average, peridotite can provide approximately 2-4 kg of H_2 per cubic meter upon oxidation. With an estimated 1,012 peridotites in Earth's upper crust (top 7 km), there is a total of 108 Mt of hydrogen that could be theoretically generated from the subsurface (Kelemen, 2011). To put this in perspective, such an amount would provide a supply of 1000 Mtpy of H_2 for 100,000 years (Osselin, 2022). As a lower-bound estimate, Smith (2005) estimated the potential hydrogen production from the Samail Ophiolite in Oman. With a total volume of ultramafic rock around 125,000 km^3, of which only 50% is serpentinized, it could provide approximately 260 Mt of hydrogen, exceeding the current world demand for one year (IEA, 2021).

From another angle, combining data from various studies, it has been estimated that the natural hydrogen being formed on Earth could account for approximately 85% of the current human-made production (Zgonnik, 2020). This estimate also has much uncertainty, and it does not consider the hydrogen already formed and stored underground or the potential of stimulated H_2 production. Therefore, these values might also underestimate the actual potential of natural hydrogen resources.

In particular, underwater subduction zones, where water supply is constant and iron exposure is frequent due to plate movements, are coupled with natural hydrogen production (Moretti *et al*., 2023). Fossil oceanic spreading centres (ophiolites) and suture zones, representing the complete subduction

PUBLISHED IN IJOG

of an ocean basin where continents collided, are also promising targets for hydrogen prospecting (Merdith *et al.*, 2020 and Liu *et al.*, 2023). On land, hydrogen seeps can often be identified by the creation of circular structures known as "fairy circles", which can serve as points of interest for natural hydrogen exploration (Myagkiy *et al.*, 2020).

One of the investigated fairy circles is first in Bourakébougou (Mali) since 2011. This natural reservoir has a diameter of more than 8 km. Prinzhofer and co-workers investigated this reservoir, confirming the presence of up to five stacked layers of high-purity hydrogen on an old cratonic basement mainly composed of pyroxene, and proposed that its industrial exploitation could be cheaper than the cost of synthetic hydrogen (Prinzhofer *et al.*, 2018). In another fairy circle of 500 m diameter in Brazil, gas flows of up to 178,000 m^3 of the release of H_2 per day were estimated (Prinzhofer *et al.*, 2018).

In Chimaera (Turkey), uninterrupted hydrogen flows have been detected for over 2,000 years (Hosgormez *et al.*, 2008). In Aragon (Spain), the presence of a significant deposit of natural hydrogen beneath the Pyrenees Mountain range has been confirmed (Lefeuvre *et al.*, 2021). Lefeuvre and colleagues studied a 10 × 10 km grid, taking and analyzing over 1,000 in situ samples to identify different hydrogen hotspots in the region. A company called Helios Aragon has been established to exploit this deposit, aiming for an annual extraction of 5.5 $x10^4$ to 7 x 10^4 metric tons per year of pure hydrogen, comparable to the production from a current steam methane reforming plant (Collodi *et al.*, 2017). It can also be seen in Figure 1 below, which explains the distribution of natural hydrogen exploration potential in the world.

Natural Hydrogen Potential in Indonesia

Indonesia possesses significant potential for natural hydrogen production, primarily due to its extensive ultramafic rock formations, which cover approximately 2.7 million hectares, making it one of the largest such areas globally (Kadarusman *et al.*, 2004). These ultramafic rocks, rich in minerals like peridotite and dunite, are integral components of ophiolite complexes. Based on Figure 2, it can

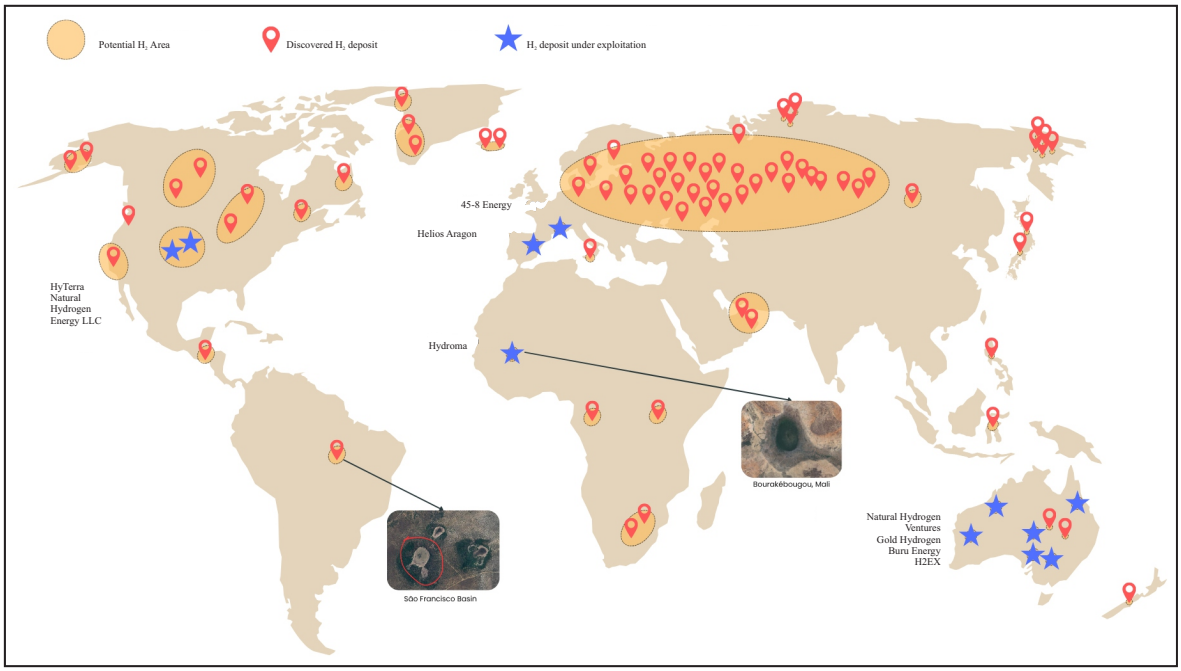


Figure 1. Detail of known natural hydrogen deposits and fairy circles. Fairy circles can be found in regions around the world with diverse diameters, locations, and densities of quartz (Source: Blay-Roger *et al.*, 2024). The black box indicates the location of natural hydrogen potential in Indonesia, which is the subject of this paper.

PUBLISHED IN IJOG

be observed that the East Sulawesi Ophiolite (ESO) is recognized as one of the three largest ophiolite complexes worldwide, extending from Gorontalo Bay through the East and Southeast Arms of Sulawesi (Kadarusman *et al*., 2004; Surono, 2012).

Recent surveys by Indonesia's Geological Agency have identified natural hydrogen occurrences in regions like Morowali and Tojo Una-Una in Central Sulawesi areas characterized by extensive ultramafic rock distributions (Geological Agency, 2024). These findings suggest that Indonesia's unique geological landscape offers promising opportunities for sustainable and clean energy development through natural hydrogen exploration.

One of the most promising locations for natural hydrogen exploration in Indonesia is the Ampana Basin, located in Central Sulawesi. This region is geologically situated within the East Sulawesi Ophiolite Belt, known for its abundance of ultramafic rocks, which are critical to hydrogen generation through serpentinization processes. Based on preliminary assessments by Indonesia's national oil company, The Ampana Basin may contain theoretical gas reserves of up to 113 trillion standard cubic feet (TSCF), making it a potentially strategic natural hydrogen site gas sampling, and field observations have revealed that this subsurface gas mixture contains up to 20 -35% natural hydrogen, co-existing with methane as a major secondary component (Sanjaya *et al*., 2024).

As illustrated in Figure 2, Sulawesi possesses a complex structural geology, marked by extensive structural geology (black lines) and the distribution of ultramafic rock formations (blue areas). Geological investigations have identified fault structures such as the Balantak Fault as key migration pathways for hydrogen from deep serpentinized ultramafic rocks toward the surface, where seeps have been observed. Similar to hydrogen systems found in Mali and Oman, this tectonically active setting and its ophiolitic basement suggest that the Ampana Basin may be part of a larger regional hydrogen system that is both naturally replenishing and economically

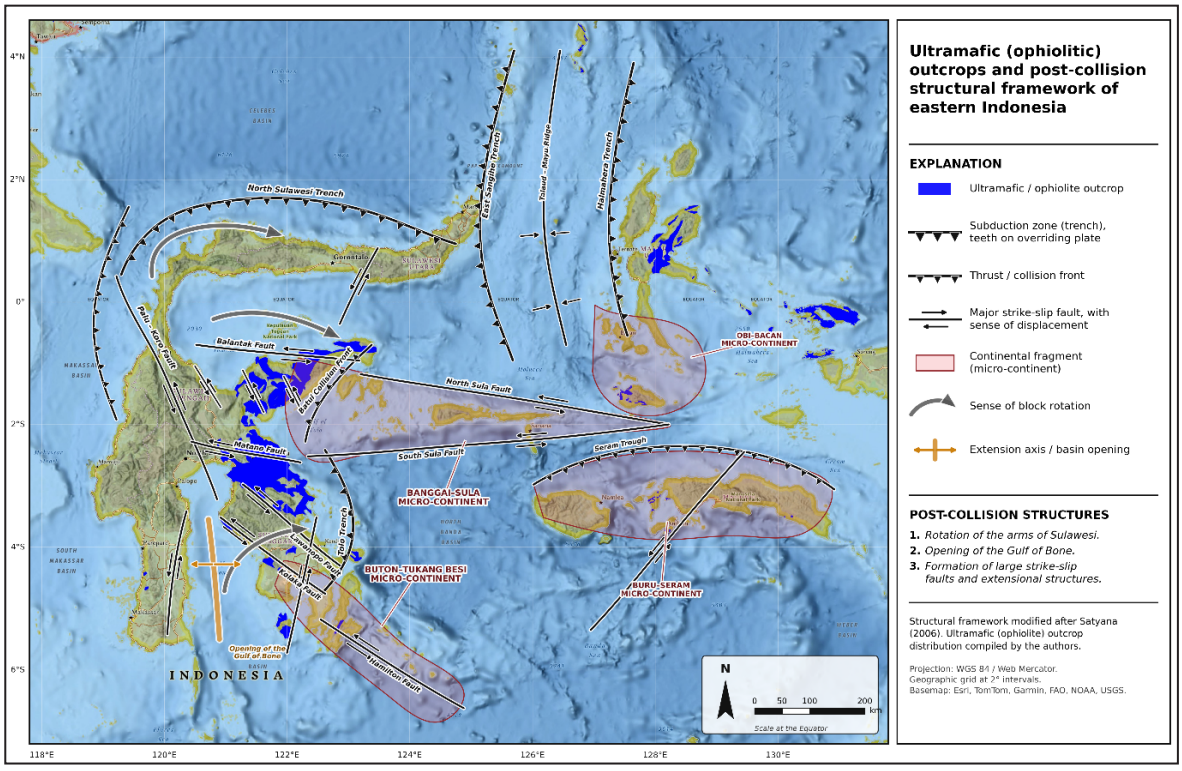


Figure 2. Ultramafic (Ophiolitic) Outcrops Map and post collision structural framework of Sulawesi Island and surrounding area. The black line gives an idea of structural geology modified from Satyana (2006), while the blue mark indicates the presence of an ultramafic outcrop.

PUBLISHED IN IJOG

viable (Prinzhofer *et al.*, 2018). Given Indonesia's commitment to clean energy transitions and the vast extent of its ultramafic terrain, the Ampana Basin could represent a cornerstone in Southeast Asia's emerging hydrogen economy.

Potential Formation

Various geological formations are capable of producing molecular hydrogen through a range of subsurface geochemical processes, including serpentinization, radiolysis, and iron oxidation. These reactions are often associated with specific rock types, particularly ultramafic and iron-rich lithologies, which serve as primary hydrogen sources due to their mineralogical composition and reactivity. In addition to their geochemical properties, the distribution and accessibility of these rocks, especially within ophiolitic belts and tectonically active regions, play a critical role in determining the viability of natural hydrogen reservoirs. The following are the types of natural hydrogen source rocks that are summarized in Table 1.

Natural Hydrogen Analogues

Analogues - Natural Seeps

Arguably, the best place to start developing understanding about natural hydrogen systems is by examining known examples of naturally occurring seeps and producing drillholes. Some continental examples have been linked to the production of hydrogen from serpentinization of ultramafic or ophiolitic complexes (Gaucher, 2020; Zgonnik, 2020). Other diffusive seeps located in intracratonic settings have been attributed to fluid-rock chemical interactions such as the oxidation of Fe^{2+}-rich minerals and lithologies in underlying rocks or radiolysis of water as outlined above (Prinzhofer *et al.*, 2018; Guelard *et al.,* 2017; Gaucher, 2020).

Figure 3 illustrates that hydrogen concentrations reach a peak within subcircular depressions, thereby confirming their status as active hydrogen seepage sites. The formation of these features is thought to result from diagenetic processes, where hydrogen increases rock porosity through chemical dissolution as it migrates towards the surface. If this hypothesis is correct, it suggests that hydrogen can migrate from deep-seated conduits, such as fault zones, through this process.

Diffusive seeps have generally been confirmed and characterized through the deployment of soil gas chemistry monitoring sensors, which indicate that hydrogen fluxes tend to vary spatiotemporally. In the case of the circular to subcircular topographic depressions, hydrogen is present within the depressions, but absent in the areas outside of and surrounding the depressions (Larin *et al.,* 2014; Zgonnik *et al.,* 2015; Prinzhofer *et al.,* 2018; Moretti *et al.,* 2021). At this stage there are no direct soil gas data indicating an active hydrogen flux at the circular structures documented in South Australia; however, gas analyses from drillholes drilled in the

Table 1. Classification of Geological Formations Contributing to Natural Hydrogen Generation and Its Occurrence Potential

Rock Type	Formation Mechanism	Global Location Potential	Potential Location in Indonesia
Ultramafic Rocks (*e.g.* peridotite, dunite)	Serpentinization: hydration and oxidation of olivine and pyroxene, releasing H_2	Samail Ophiolite (Oman), New Caledonia, Pyrenees (Spain), Turkey	East Sulawesi Ophiolite, Morowali, Tojo Una-Una (Sulawesi)
Iron-rich Silicate Rocks (*e.g.* fayalite-bearing rocks)	Oxidation of Fe^{2+} in silicates by water, forming magnetite and H_2	Kansas (USA), Witwatersrand Basin (South Africa), Russia	Potentially in Sulawesi ultramafic belts
Radioactive Rocks (*e.g.* granites, metamorphic basement rocks)	Radiolysis of water due to natural radioactive decay of U, Th, K	Canadian Shield, Fennoscandian Shield (Finland), South Africa	Possibly in ancient crystalline basement areas
Ophiolite Complexes	Combination of serpentinization and fault-driven fluid flow	Oman, New Caledonia, the Alps, and the Zagros Mountains	East and Southeast Sulawesi (East Sulawesi Ophiolite Belt)
Nickel/Carbon-rich Ultramafic Rocks	Catalytic enhancement of serpentinization at low temperatures	Peridotite zones in Oman, Eastern Europe	Areas within nickel-rich ultramafic zones in Sulawesi
Banded Iron Formations (BIFs)	Oxidation of Fe^{2+} in iron-rich sedimentary layers under anoxic conditions, producing H_2	Kaapvaal Craton (South Africa), Pilbara (Australia), Canadian Shield	Possible analogues in pre-Tertiary formations in Kalimantan or Papua (requires further study)

PUBLISHED IN IJOG

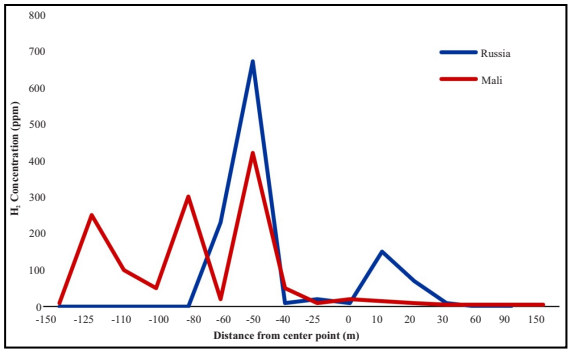


Figure 3. Examples of natural hydrogen seeps from shallow, circular to subcircular topographic depressions (aka fairy circles) and associated measured surface hydrogen concentration in Russia and Mali (Source: Larin *et al.,* 2014; Prinzhofer *et al.*, 2018).

1920s-30s on Kangaroo Island (American Beach Bore 1) and Yorke Peninsula (Ramsay Oil Bore 1) provide alternative evidence that a hydrogen resource may be present in these locations (Ward 1932a, 1932b, 1941).

A recent study by Frery *et al.* (2021) demonstrated that a series of similar circular structures, spatially related to The Darling Fault in The North Perth Basin, Western Australia, are natural hydrogen seepages. In this location, The Darling Fault juxtaposes Precambrian ultramafic and mafic rocks and Proterozoic Fe-rich granite of The Yilgarn Craton against layered Permo-Mesozoic sedimentary rocks which include multiple aquifers and aquitards.

Analogues - High Hydrogen Fluxes in Drillholes and Mines

There are also numerous examples of groundwater, oil and gas drillholes and mines intersecting significant hydrogen fluxes or accumulations in a range of cratonic settings, including Russia (Larin *et al.,* 2014); Brazil (Prinzhofer *et al.,* 2019); Bourakebougou, Mali (Prinzhofer *et al.,* 2018); northeastern Kansas, USA (Coveney *et al.,* 1987; Guelard *et al.,* 2017); The Witwatersrand, South Africa; Canada; and Finland. A number of authors have noted the similarity between the development of the hydrocarbons industry and the current state of knowledge about natural hydrogen. A possible analogue and reasonable starting point to developing an exploration strategy, then, might be the petroleum systems (source-migration pathway-reservoir-seal-preservation) approach that underpins hydrocarbon exploration (Magoon and Dow, 1994).

Exploitation of Geological Hydrogen

The extraction of natural hydrogen can be carried out by adapting technology currently employed for natural gas extraction (ENGIE Innovation, 2023). Briefly, once the potential reservoir is confirmed by seismic techniques, a drilling rig is used to penetrate rock layers, while pipes are employed to facilitate the drilling.

The continuous circulation of mud helps control the temperature and pressure throughout the drilling process. During this process, various issues can occur, such as the loss of recirculated mud through infiltration into the rock, mud contamination, or pipe blockages. These problems can be minimized by selecting an appropriate drilling path and periodically checking the quality of the recirculated mud during drilling. Once the gas reservoir is reached, the pipes are lined with dense concrete to minimize gas migration and ensure structural integrity (Gold Hydrogen, 2023). It is especially important to ensure the structural integrity of the installation by respecting the concrete drying times and operating with caution due to the reactive and diffusive nature of hydrogen. A leak at low depths can be dangerous due to the potential to form flammable and explosive mixtures with O_2.. High-pressure valves are employed to control the extraction and maintain pressure within the reservoir.

Once the pipes are in place, extracting hydrogen becomes relatively straightforward (ENGIE Innovation, 2023). Extraction occurs through pipelines installed in the perforated rock, using the pressure of the pressurized hydrogen (usually >500 bar) to fill tanks for small-scale distribution. However, there are currently no companies dedicated to this enhanced or stimulated extraction of hydrogen, making it difficult to provide details.

Hydrogen possesses high molecular diffusivity, which makes large-scale storage of synthetic

PUBLISHED IN IJOG

hydrogen a major challenge (Tarhan and Çil, 2021). Cryogenic tanks and pipelines are used for small-scale distribution and immediate consumption. Alternatively, underground geological structures like salt caverns are being investigated as large-scale hydrogen storage facilities (Zivar *et al.,* 2021). These are cavities formed by the dissolution of salt deposits in thick salt beds or domes deep underground (Aftab *et al*., 2022). They can provide secure and isolated storage environments, as the salt walls act as natural barriers against leakage (Lankolf *et al*., 2022).

Moreover, the plasticity of salt enables the caverns to withstand high pressures without collapsing, creating an ideal environment for hydrogen storage (Watkins *et al*., 2022). Efforts are underway to locate suitable natural salt deposits, and countries like Poland are starting to develop an industry around this concept (Tarkowski, 2017). Overall, large-scale hydrogen storage is a subject of significant industrial interest. Since natural hydrogen is stored in geological traps, the discovery of natural hydrogen deposits could not only provide the value of the hydrogen within them, but also the value of the reservoir itself.

One drawback of natural hydrogen can be its purity. Although deposits with very high purity have been found, impurities are frequently present (Neal and Stanger, 1983), including gases such as nitrogen, methane, or unreacted CO_2, as well as moisture. The purity of natural hydrogen largely depends on the quality of the water that reached the reactive rock. Water often contains particles, carbonates, and CO_2 that can produce organic impurities through Fischer-Tropsch mechanisms, as the pressure, temperature, and composition of the rock favour such reactions (Peter, 1989). Therefore, processing this gas may require the use of desiccants and separation of light gases using membranes, cryogenic distillation, or pressure swing adsorption (Adhikari and Fernando, 2006). While separation costs could rapidly increase the production cost of natural hydrogen from some locations, certain impurities (*e.g*., CH_4) could also have market value.

Natural Hydrogen Reservoirs Worldwide

Recent investigations into natural hydrogen reservoirs also highlighted the occurrence of methane that influences its purity and downstream processing requirements. The following presents a representative case study of a natural gas well exhibiting a promising concentration of hydrogen, which may serve as a reference for further geochemical and reservoir analyses.

Table 2 provides a comparative overview of natural hydrogen concentrations from multiple sites across the globe. These samples represent various geological settings, predominantly associated with serpentinized ultramafic and mafic rock, revealing the natural occurrence of molecular hydrogen in differing concentrations, along with co-produced gases like methane.

From the table, it is evident that most hydrogen-rich samples are linked to ophiolitic and ultramafic systems undergoing serpentinization, a geochemical process that facilitates hydrogen production. These findings support the growing interest in serpentinite-hosted hydrogen systems as potential sources of clean energy and underscore the variability in hydrogen yield across different geological contexts.

This compilation of studies in Table 3 reveals how diverse experimental settings and methodologies affect hydrogen production rates. Figure 4 further demonstrates the large variability in experimental H_2 yields across the temperature range, including within the commonly favorable serpentinization window of 200-320 °C. This variability highlights the combined influence of temperature, mineralogy, pressure, and experimental conditions on H_2 generation. These findings provide a basis for predicting hydrogen production under natural conditions and guiding exploration using thermodynamic indicators and mineral reactivity patterns.

Discussion

This study confirms Indonesia's significant potential as a natural hydrogen hotspot, which

PUBLISHED IN IJOG

Table 2. Hydrogen and Methane Concentrations in Natural Gas Samples from Various Geological Settings Worldwide and Its Occurrence Potential and Its Occurrence Potential

Sample name	Country	H_2	CH_4	Rock type and main features	Mafic-Ultramafic System
		mL/kg	mL/kg		
Chim Per 1	Turkey	16.180	0.002	Serpentinized harzburgite (Chimaera seep site)	Tekirova ophiolite
Tek Per	Turkey	11.200	0.180	Serpentiniz. dunite (Cirali beach, 3 km from Chimaera)	Tekirova ophiolite
CEDB105B	Brazil	10.200	0.266	Heavily altered chromitite	Pilar de Goias, G. Belt
MSK 2	Greece	12.100	1.520	Chromitite in serpentinised harzburgite-lherzolite, thrust	Othrys ophiolite
MET 2	Greece	4.560	0.274	Chromitite with interstitial serpentine and magnetite	Othrys ophiolite
MK 1	Greece	0.092	0.008	Basalt	Othrys ophiolite
Austin Creek	USA	15.7 %	15.8 %	Ultra-basic springs (serpentinization)	Ophiolite
Camp Spring	USA	50.9 %	7.4 %	Ultra-basic springs (serpentinization)	Ophiolite
Bahla, 97	Oman	81 -97 %	0.9-2.2 %	Gas seeps on the surface at Ain Al-Waddah.	Ophiolite
Nizwa, 99	Oman	22 -99 %	4%	Bubbles in springs (Fe^{2+} oxidation by water)	Ophiolite
Mt. Lanat	Philippines	45.6 %	53.8 %	Burning gas in peridotites of the Zambales ophiolite complex	Ophiolite
Nagsasa	Philippines	58.5 %	38.7 %	Free gases seep on the surface	Ophiolite
Penneshaw	Australia	68.6 %	4.68 %	Reaction of water with ferrous compounds or magmatic (from high-temperature reactions)	Precambrian rocks
Minlanton	Australia	84 %	NA	Gas from a well drilled into Precambrian metamorphic rocks.	Precambrian rocks
Les Tiogaux	France	14.1 %	NA	Gas from a mofetta (gas seep)	Geyser
Wittelsheim	France	>50 %	NA	Main component of the gas in a potash deposit	Salt deposits
Ampana Basins, Tojo Una-Una	Indonesia	20 -35	13.4 %	Ultramafic rocks serpentinization	Ophiolite melange
Bahodopi, Morowali	Indonesia	9 %	16.9 %	Ultramafic rocks serpentinization	Ophiolite melange

is fundamentally supported by its unique geological conditions. The extensive East Sulawesi Ophiolite Formation (ESO) provides an ideal environment for hydrogen production through serpentinization of ultramafic rocks. Tangible evidence of this potential was found in the Ampana Basin, where methane gas samples showed hydrogen concentrations of up to 35%. The combination of abundant source rocks, active formation processes, and efficient migration pathways forms a highly promising natural hydrogen system.

Despite the promising outlook, the exploitation of natural hydrogen in Indonesia faces technical challenges, particularly regarding gas purity due to the presence of impurities such as methane and nitrogen. The presence of these gases requires purification technology that can impact production costs, although some impurities, such as methane, also have potential market value. Therefore, moving forward requires more focused exploration efforts, including extensive geophysical and geochemical surveys, pilot drilling projects, and the development of a supportive regulatory framework. By overcoming these challenges, Indonesia can elevate its status from theoretical potential to proven reserves, positioning it as a leader in the emerging global clean energy frontier.

The data presented in Table 3 reveal vast variability in the hydrogen generation rates. This demonstrates that natural hydrogen is highly dependent on specific environmental conditions. The rates can be broadly categorized as follows:

- A low generation rate is commonly associated with low-temperature and low-pressure conditions, with generation rates of 0.01 - 1 mmol/kg. This phenomenon has been proven by a number of studies like McCollom and Donaldson (2016), Neubeck *et al*. (2011), and Okland *et al*. (2014).
- A moderate to high generation rate that is associated with hydrothermal conditions (200 -300$^{\circ C)}$ is considered the optimal condition for serpentinization. This condition

PUBLISHED IN IJOG

Table 3. Summary of Previous Studies on Natural Hydrogen Generation Under Various Experimental and Geological Conditions

Study	H_2	Conditions	Mineral/Grain Size	Method
Leshounova (1991)	37.42 cm^3/kg	100°C; 8 MPa	Limestone	Experimental
Abrajano *et al.* (1988)	8.4 vol. %	110 -125°C	Zambales ophiolite (LFE-1)	Isotopic Analysis
Abrajano (1988)	42.3 vol. %	110 -125°C	Zambales ophiolite (LFE-2)	Isotopic Analysis
Abrajano (1988)	42.6 vol. %	110 -125°C	Zambales ophiolite (LFE-3)	Isotopic Analysis
Neal and Stanger (1983)	0.1-99 vol. %	20 -50°C	Ultramafic rocks	Mass spectrometry and gas chromatography
Jeffrey and Kaplan (1988)	2.7-8.0 vol. %	50°C	Granite	Drilling method experiments
Berndt *et al*. (1996)	25 mmol/kg	400°C, 500 bar	Olivine and pyroxene (60 µm)	Lab experiment
Berndt *et al.* (1996)	158 mmol/kg	300°C, 500 bars	Olivine (30-80 µm)	Lab experiment
Berndt *et al.* (1996)	1.7 mmol/kg	300°C, 500 bars	Olivine	Lab experiment
Grozeva *et al*. (2017)	22 mmol/kg	200-300°C, 350 bars	Forsterite, <44 µm	Lab experiment
Grozeva *et al*. (2017)	65 mmol/kg	300°C, 350 bars	Harzburgite (63-125 µm)	Lab experiment
Huang *et al.* (2019)	119 mmol/kg	300°C, 3 kilobars	Peridotite (< 30 µm)	Lab experiment
Huang *et al*. (2019)	79.6 mmol/kg	300°C, 3 kilobars	Olivine (<30 µm)	Lab experiment
Huang *et al*. (2019)	244 mmol/kg	300°C, 3 kilobars	Olivine (>250 µm)	Lab experiment
Jones *et al*. (2010)	12 mmol/kg	200°C, 300 bars	Olivine (100um)	Lab experiment
Marcaillou *et al.* (2011)	14 mmol/kg	300°C, 300 bars	Peridotite (~1 µm)	Lab experiment
Mayhew *et al*. (2018)	0.04 mmol/kg	55°C, low pressure	Peridotite (53-212 µm)	Lab experiment
Mayhew *et al.* (2018)	0.3 mmol/kg	100 ° C, low pressure	Peridotite (53-212 µm)	Lab experiment
McCollom and Seewald (2007)	74 mmol/kg	300°C, 350 bars	Olivine (fine powder)	Lab experiment
McCollom and Donaldson (2016)	0.2 mmol/kg	90°C, near-surface	Olivine (53-212 µm)	Lab experiment
McCollom *et al*. (2020)	105 mmol/kg	230 °C, 350 bars	Olivine (80%) and pyroxene (20%) (38-212 um)	Lab experiment
Miller *et al.* (2017)	12 mmol/kg	100°C, low pressure	Dunite (53-212 µm)	Lab experiment
Miller *et al.* (2017)	18.9 mmol/kg	200 °C, 300 bars	Dunite (30-63 µm)	Lab experiment
Neubeck *et al*. (2011)	0.5-1.5 mmol/kg	30-70 °C, low pressure	Olivine (0.250 and 0.500 mm)	Lab experiment
Okland *et al.* (2014)	0.012 mmol/kg	25°C, low pressure	Dunite (<63 µm)	Lab experiment
Fauguerolles (2016)	Not quantified	250-350 °C, 50 MPa	Harzburgite	Experimental
Huang *et al.* (2020)	Order of magnitude decrease (pyroxene)	311-500 °C, 3 kbar	Olivine + pyroxene/spinel	Experimental
Huang *et al.* (2023)	67-89 vol%	300 °C, 2.2-3.4 kbar	Olivine, peridotite	Experimental
McCollom *et al*. (2020)	Sharp pH-dependence	200-230 °C	Olivine + orthopyroxene	Experimental
Vega *et al.* (2024)	9-13 vol%	80-245 °C	Olivine sand (250-355 µm)	Experimental
Zhang *et al.* (2015)	Variable, less from basalt	300-500 °C, 1-3 kbar	Mixed:peridotite, basalt	Experimental
Albers *et al*. (2019)	200-350 mmol/kg	25-400 °C	Cratonic/peridotite	Modeling
McCollom and Bach (2009)	360 mmol/kg	NA	Peridotite, pyroxenite	Thermodynamic Modeling
Klein *et al*. (2013)	200-340 mmol/kg	NA	Olivine	Geochemical Modeling
Klein *et al.* (2013)	50 -150 mmol/kg	NA	Olivine	Modeling
Donval *et al.* (1997)	13 mmol/kg	NA	NA	MOR (Rainbow hydrothermal field at Mid-Atlantic ridge)
Charlou *et al*. (2002)	16 mmol/kg	NA	NA	MOR (Rainbow hydrothermal field at Mid-Atlantic ridge)
Kelley *et al.* (2005)	15 mmol/kg	NA	NA	MOR (Lost City Hydrothermal Field)
Etiope (2024)	0.72 mmol/kg	NA	Dunite	Extraction

generally can produce up to 1 -100 mmol/kg hydrogen, according to Jones *et al.* (2010) and McCollom and Seewald (2007).

- Very high generation rates typically occur under high-pressure and high-temperature experimental conditions or are predicted by thermodynamic models. This category can produce up to 100-360 mmol/kg hydrogen, as proven by Berndt *et al.* (1996), Huang *et al.* (2019), and McCollom and Bach (2009).

This variability is systematically controlled by a suite of geological and chemical factors. The rate of hydrogen generation is determined by a complex interaction of the following key

PUBLISHED IN IJOG

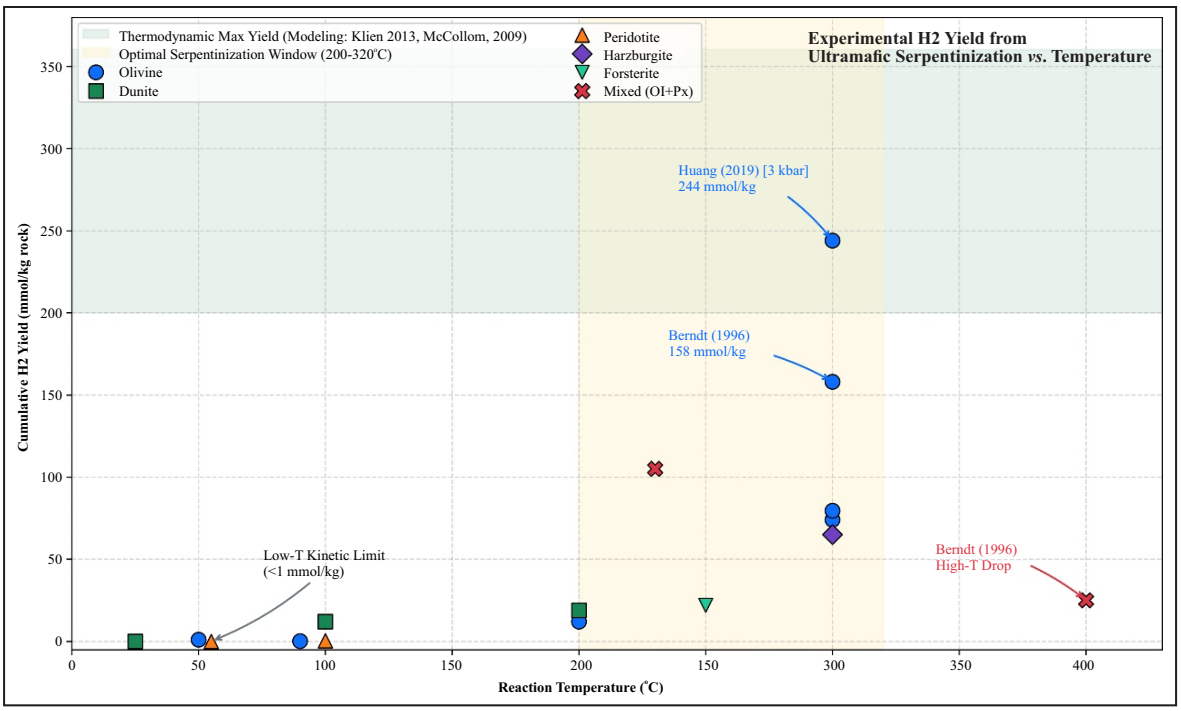


Figure 4. Experimental H_2 yields during ultramafic serpentinization as a function of temperature and mineral composition.

parameters summarized in Table 4 below.

- The crucial point is that the hydrogen generation rate depends on the reaction kinetics of the system. Consequently, exploration efforts should concentrate on areas where these factors are optimized in order to identify locations with high-flux natural hydrogen.
- The geological source can be identified by focusing on regions with abundant, fresh, or partially serpentinized ultramafic rocks, such as ophiolites and greenstone belts.
- The reaction engine can be identified by detecting areas with a sustained heat source within the optimal temperature range of 200

Table 4. Summary of Factors Controlling the Rate of Natural Hydrogen Generation During Serpentinization

Aspect	Parameter	Impact
Temperature	Low temperature (<100°C)	Reactions are extremely slow with minimum production of hydrogen. (*e.g.* McCollom and Donaldson, 2016: 0.2 mmol/kg).
	Optimal temperature (200–315°C)	Geochemical reactions proceed at an optimum rate with significant production of hydrogen. (*e.g.* Berndt *et al.*, 1996: 158 mmol/kg).
	Very high temperature (>400°C)	Stability fields of minerals change, and hydrogen rates can actually decrease (as indicated in Huang *et al.*, 2023).
Pressure	Reaction enabler	High pressure helps keep water in a supercritical state at high temperatures, facilitating the water-rock interaction.
	Mechanism controller	High pressure and confining stress can reduce rock permeability and fracture networks.
Mineralogy	Rock type	Ultramafic rocks (*e.g.* dunite, harzburgite) are richer in iron-bearing olivine than mafic rocks like basalt. (*e.g.* Zhang *et al.*, 2015).
	Iron content	Rocks with higher initial Fe^{2+} content have a higher potential hydrogen yield.
	Grain Size and Surface Area	Finely crushed or powdered samples in experiments react much faster due to a vastly increased surface area for reaction.
Fluid chemistry	pH	Serpentinization drives fluids to highly alkaline conditions (pH > 10), which can passivate mineral surfaces and slow the reaction (McCollom *et al.*, 2020).
	Salinity	High salinity can significantly reduce hydrogen diffusivity and may also affect reaction kinetics.
	Catalyst	The presence of certain minerals can catalyse reactions. (*e.g.*, nickel-rich ultramafic rocks).
Time	NA	Geological processes operate over millions of years. Continuous reaction over a vast volume of rock (*e.g.* the entire Samail Ophiolite) can produce enormous quantities of hydrogen.

PUBLISHED IN IJOG

-315°C, typically generated by deep-seated tectonic activity or radioactive decay.
- The geological plumbing system can be mapped by identifying fault and fracture systems that act as conduits for the migration and accumulation of water and hydrogen.
- Surface indicators of an active system at depth can be identified through the presence of direct evidence, including "fairy circles" or hydrogen seeps.

Conclusions

This review highlights the vast potential of natural hydrogen as a clean, economically viable, and geologically abundant energy resource. Through the analysis of various global formations and geological mechanisms, particularly serpentinization, this study affirms the continuous and natural generation of hydrogen in the Earth's subsurface. Compared to conventional hydrogen production methods, natural hydrogen offers superior cost advantages, with production estimates as low as USD 0.50 per kilogram, and minimal carbon emissions, making it a strong candidate for sustainable energy systems. However, the presence of impurities such as methane, nitrogen, and oxygen necessitates the implementation of purification technologies, which may affect cost and feasibility in certain settings. The Indonesian Archipelago, due to its complex tectonic structure and the presence of ultramafic rocks, holds promise as a natural hydrogen hotspot. Nevertheless, further geophysical exploration, regulatory frameworks, and technological investments are required to unlock this potential. As the world seeks low-carbon energy pathways, integrating natural hydrogen into Indonesia’s energy portfolio could significantly contribute to both national and global sustainability goals.

This study emphasizes Indonesia's significant potential due to its extensive ultramafic terranes, which serve as the source rock, located in a tectonically active region that acts as the engine and potential conduit for hydrogen generation. The documented hydrogen seeps in Sulawesi, which contain 20 -35% hydrogen, demonstrate that these systems are not only theoretically capable of producing hydrogen but are also actively generating and leaking hydrogen in the present day. The next step is to identify where the generated hydrogen has accumulated in commercially viable quantities.

Acknowledgement

The authors would like to express their sincere gratitude to the Department of Chemical Engineering, Universitas Indonesia for providing institutional support and facilities during the preparation of this article. The authors also wish to acknowledge New Venture-Pertamina Hulu Energi (PHE) for their support and for the valuable discussions and insights that contributed to the understanding of natural hydrogen potential in Indonesia, particularly regarding the East Sulawesi Ophiolite region.

References

Abrajano, T.A., Pasteris, J.D., and Bacuta, G.C. 1988. Zambales ophiolite, Philippines I. Geology and petrology of the critical zone of the Acoje massif. *Tectonophysics*, 168 (1-3), p.65-100. DOI: 10.1016/0040-1951(89)90369-7.

Adhikari, S. and Fernando, S., 2006. Hydrogen membrane separation techniques. *Industrial and Engineering Chemistry Research*, 45 (3), p.875-881.

Aftab, A., Hassanpouryouzband, A., Xie, Q., Machuca, L.L., and Sarmadivaleh, M., 2022. Toward a fundamental understanding of geological hydrogen storage. *Industrial and Engineering Chemistry Research*, 61 (9), p.3233-3253. DOI: 10.1021/acs.iecr.1c04380.

Albers, E., Schroeder, T., and Bach, W., 2019. Melt impregnation of mantle peridotite facilitates high-temperature hydration and

PUBLISHED IN IJOG

mechanical weakening: Implications for oceanic detachment faults. *Geochemistry, Geophysics, Geosystems,* 20, p.84-108. DOI: 10.1029/2018GC007783.

Bagreev, A., Menendez, JA., Dukhno, I., Tarasenko, Y., and Bandosz, T.J., 2004. Bituminous coal-based activated carbons modified with nitrogen as adsorbents of hydrogen sulphide. *Carbon,* 42, p.469-476. DOI: 10.1016/j.carbon.2003.10.042.

Berndt, M.E., Allen, D.E., and Seyfried, W.E. Jr., 1996. Reduction of CO_2 during serpentinization of olivine at 300°C and 500 bar. *Geology,* 24 (4), p.351-354. DOI: 10.1130/0091-7613(1996)024<0351:ROCDSO>2.3.CO; 2.

Blay-Roger, R., Bach, W., Bobadilla, L.F., Ramirez Reina, T., Odriozola, J.A., Amils, R., and Blay, V., 2024. Natural hydrogen in the energy transition: Fundamentals, promise, and enigmas. *Renewable and Sustainable Energy Reviews,* 189 (Part A), 113888. DOI: 10.1016/j.rser.2023.113888.

Bourdet, J., Piane, D.C., Wilske, C., Mallants, D., Suckow, A., Questiaux, D., Gerber, C., Crane, P., Deslandes, A., Martin, L., and Aleshin, M., 2023. Natural hydrogen in low-temperature geofluids in a Precambrian granite, South Australia. Implications for hydrogen generation and movement in the upper crust. *Chemical Geology,* 638, 121698. DOI: 10.1016/j.chemgeo.2023.121698.

Charlou, J., Donval, J., Fouquet, Y., Jean-Baptiste, P., Holm, N., 2002. Geochemistry of high H_2 and CH4 vent fluids issuing from ultramafic rocks at the Rainbow hydrothermal field (36° 14′ N, MAR). *Chemical Geology,* 191, p.345-359. DOI: 10.1016/S0009-2541(02)00134-1.

Collodi, G., Azzaro, G., Ferrari, N., and Santos, S., 2017. Techno-economic evaluation of deploying CCS in SMR-based merchant H_2 production with NG as feedstock and fuel. *Energy Procedia,* 114, p.2690-2712. DOI: 10.1016/j.egypro.2017.03.1533.

Coveney, R.M.J., Goebel, E.D., Zeller, J., Dreschhoff, G.A.M., and Angino, E.E., 1987. Serpentinization and the origin of hydrogen gas in Kansas. *AAPG Bulletin,* 71, p.39-45. DOI: 10.1306/94886D3F-1704-11D7-8645000102C1865D.

CSIRO, 2024. *Natural hydrogen - Subsurface Fluid Processes*. https://research.csiro.au/ugre/natural-hydrogen-2/.

Demouchy, S., 2010. Diffusion of hydrogen in olivine grain boundaries and implications for the survival of water-rich zones in the earth mantle. *Earth and Planetary Science Letters,* 295, p.305-313. DOI: 10.1016/j.epsl.2010.04.019.

Donval, J.P.,Charlou, J.L., Douville, E., Knoery, J., Fouquet, Y., Poncevera, E., Jean-Baptiste, P., Stievenard, M., and German. C., 1997. Geochemistry of high H_2 and CH_4 content in hydrothermal fluids from the Rainbow site newly sampled at 36° 14' N on the AMAR Segment, Mid-Atlantic Ridge (Diving FLORES cruise, July 1997): Comparison with other MAR sites. *Chemical Geology*, 78, 46-F832.

ENGIE Innovation, 2023. H_2 in the underground: are salt caverns the future of hydrogen storage? Retrieved from http://innovation.engie.com/en/news/news/did-you-know-/hydrogen-underground-storage-salt-caverns/25906.

Etiope, G., 2024. Natural hydrogen extracted from ophiolitic rocks: A first dataset. *International Journal of Hydrogen Energy,* 78, p.368-372. DOI: 10.1016/j.ijhydene.2024.06.292.

Farver, J.R., 2010. Oxygen and hydrogen diffusion in minerals. *Reviews in Mineralogy and Geochemistry,* 72, p.447-507. DOI: 10.2138/rmg.2010.72.10.

Fauguerolles, C., 2016. Experimental study of H_2 generation associated with peridotite serpentinization at slow spreading ridges. [Doctoral dissertation, Université d'Orléans]. HAL Theses. https://theses.hal.science/tel-01549129.

Firstov, P. and Shirokov, V., 2005. Dynamics of molecular hydrogen and its relation to deformational processes at the Petropavlovsk-Kamchatskii geodynamic test site: Evidence from observations in 1999-2003. *Geochemistry International,* 43, p.1056-1064.

PUBLISHED IN IJOG

Frery, E., Langhi, L., Maison, M., and Moretti, I., 2021. Natural hydrogen seeps identified in the North Perth Basin, Western Australia. *International Journal of Hydrogen Energy,* 46 (61), p.31158-31173. DOI: 10.1016/j.ijhydene.2021.07.023.

Gaucher, E.C., 2020. New perspectives in the industrial exploration for native hydrogen. *Elements,* 16 (1), p.8-9. DOI: 10.2138/gselements.16.1.8.

Geological Agency, 2024. Survei Natural Hydrogen di East Sulawesi Ophiolite. https://geologi.esdm.go.id/media-center/survei-natural-hydrogen-di-east-sulawesi-ophiolite.

Gold Hydrogen, 2023. Natural hydrogen exploration drilling and well testing. https://www.goldhydrogen.com.au/ramsay-project/.

Grozeva, N.G., Klein, F., Seewald, J.S., and Sylva, S.P., 2017. Experimental study of carbonate formation in oceanic peridotite. *Geochimica et Cosmochimica Acta,* 199, p.264-286. DOI: 10.1016/j.gca.2016.10.052.

Guelard, J., Beaumont, V., Rouchon, V., Guyot, F., Pillot, D., Jézéquel, D., Ader, M., Newell, D., and Deville, E., 2017. Natural H_2 in Kansas: deep or shallow origin? Geochemistry, Geophysics, Geosystems, 18 (5), p.1841-1865. DOI: 10.1002/2016GC006544.

Hosgörmez, H., 2007. Origin of the natural gas seep of Çirali (Chimera), Turkey: Site of the first Olympic fire. *Journal of Asian Earth Sciences,* 30, p.131-141. DOI: 10.1016/j.jseaes.2006.08.002.

Hoskin, C.M. and Sundeen, D.A., 1985. Grain size of granite and derived grus, Enchanted Rock pluton, Texas. *Sedimentary Geology,* 42, p.25-40. DOI: 10.1016/0037-0738(85)90071-5.

Huang, R., Sun, W., Song, M., and Ding, X., 2019. Influence of pH on Molecular Hydrogen (H_2) Generation and Reaction Rates during Serpentinization of Peridotite and Olivine. *Minerals,* 9 (11), 661pp. DOI: 10.3390/min9110661.

Huang, R., Sun, W., Ding, X., Zhao, Y., and Song, M., 2020. Effect of pressure on the kinetics of peridotite serpentinization. *Physics and Chemistry of Minerals,* 47 (7), 33pp. DOI: 10.1007/s00269-020-01101-x.

Huang, Y., Nakatani, T., Sawa, S., Wu, G., Nakamura, M., and McCammon, C., 2023. Effect of faceting on olivine wetting properties. *American Mineralogist,* 108 (12), p.2244-2259. DOI: 10.2138/am-2022-8808.

Hutchinson, I.P., Jackson, O., Stocks, A.E., Barnicoat, A.C., and Lawrence, S.R., 2024. Greenstones as a source of hydrogen in cratonic sedimentary basins. *Geological Society, London, Special Publications,* 547. DOI: 10.1144/SP547-2023-39.

International Energy Agency/IEA, 2021. *Global Hydrogen Review 2021* - Executive summary. https://www.iea.org/reports/global-hydrogen-review-2021/executive-summary.

Jackson, O., Lawrence, S.R., Hutchinson, I.P., Stocks, A.E., Barnicoat, A.C., and Powney, M., 2024. Natural hydrogen: sources, systems and exploration plays. *Geoenergy,* 2 (1), p.1-9. DOI: 10.1144/geoenergy2024-002.

Jeffrey, A.W.A. and Kaplan, I.R., 1988. Hydrocarbons and inorganic gases in the Gravberg-1 well, Siljan Ring, Sweden. *Chemical Geology,* 71, p.237-255.

Jones, L.C., Rosenbauer, R., Goldsmith, J.I., and Oze, C., 2010, Carbonate control of H_2 and CH4 production in serpentinization systems at elevated P-Ts, Geophys. *Geophysical Research Letters,* 37, L14306, DOI: 10.1029/2010GL043769.

Kadarusman, A., Miyashita, S., Maruyama, S., Parkinson, C.D., and Ishikawa, A., 2004. Petrology, geochemistry and paleogeographic reconstruction of the East Sulawesi Ophiolite, Indonesia. *Tectonophysics,* 392 (1-4), p.55-83.

Kelemen, P.B., Matter, J., Streit, E.E., Rudge, J.F., Curry, W.B., and Blusztajn, J., 2011. Rates and mechanisms of mineral carbonation in peridotite: natural processes and recipes for enhanced, in situ CO_2 capture and storage. *Annual Review of Earth and Planetary Sciences,* 39 (1), p.545-576. DOI: 10.1146/annurev-earth-092010-152509.

PUBLISHED IN IJOG

Kelley, D.S., Karson, J.A., Fruh-Green, G.L., Yoerger, D.R., Shank, T.M., Butterfield, D.A., Hayes, J.M., Schrenk, M.O., Olson, E.J., and Proskurowski, G., 2005. A serpentinite-hosted ecosystem: The Lost City hydrothermal field. *Science,* 307, p.1428-1434. DOI: 10.1126/science.1102556.

Keshavarz, A., Abid, H., Ali, M., and Iglauer, S., 2022. Hydrogen diffusion in coal: Implications for hydrogen geo-storage. *Journal of Colloid and Interface Science,* 608, p.1457-1462. DOI: 10.1016/j.jcis.2021.10.050.

Klein, F., Bach, W., and McCollom, T.M., 2013. Compositional controls on hydrogen generation during serpentinization of ultramafic rocks. *Lithos,* 178, p.55-69. DOI: 10.1016/j.lithos.2013.03.008.

Lankof, L., Urbańczyk, K., and Tarkowski, R., 2022. Assessment of the potential for underground hydrogen storage in salt domes. *Renewable and Sustainable Energy Reviews,* 160, 112309. DOI: 10.1016/j.rser.2022.112309.

Larin, N., Zgonnik, V., Rodina, S., Deville, E., Prinzhofer, A., and Larin, V.N., 2014. Natural molecular hydrogen seepage associated with surficial, rounded depressions on the European craton in Russia. *Natural Resources Research,* 24, p.369-383. DOI: 10.1007/s11053-014-9257-5.

Lefeuvre, N., Truche, L., Donzé, F.V., Ducoux, M., Barré, G., Fakoury, R.A., 2021. Native H_2 exploration in the western Pyrenean foothills. *Geochemistry*. https://essopenarchive.org/doi/full/.

Levshounova, S.P., 1991. Hydrogen in petroleum geochemistry. *Terra Nova,* 3, p.579-585. DOI: 10.1111/j.1365-3121.1991.tb00199.x.

Li, J. and Chou, I.M., 2015. Hydrogen in silicate melt inclusions in quartz from granite detected with Raman spectroscopy. *Journal of Raman Spectroscopy,* 46 (10), p.983-986.DOI: 10.1002/jrs.4644.

Liu, J., Wang, S., Javadpour, F., Feng, Q., and Cha, L., 2022. Hydrogen diffusion in clay silt: Implications for the geological storage. *Energy and Fuels,* 36, p.7651-7660. DOI: 10.1021/acs.energyfuels.2c01189.

Liu, Z., Perez-Gussinyé, M., García-Pintado, J., Mezri, L., and Bach, W., 2023. Mantle serpentinization and associated hydrogen flux at North Atlantic magma-poor rifted margins. *Geology,* 51 (3), p.284-289. DOI: 10.1130/G50722.1.

Magoon, L.B. and Dow, W.G., 1994. The petroleum system. *In*: L.B. Magoon and W.G. Dow (eds), The petroleum system - from source to trap. *AAPG Memoir* 60, p.3-24. M60585.

Marcaillou, C., Munoz, M., Vidal, O., Parra, T., Harfouche, M., 2011. Mineralogical evidence for H_2 degassing during serpentinization at 300 °C/300 bar. *Earth Planetary Science Letters,* 303, p.281-290. DOI: 10.1016/j.epsl.2011.01.006.

Mayhew, L.E., Ellison, E.T., Miller, H.M., Kelemen, P.B., and Templeton, A.S., 2018. Iron transformations during low-temperature alteration of variably serpentinized rocks from the Samail ophiolite, Oman. *Geochimica et Cosmochimica Acta,* 222, p.704-728. DOI: 10.1029/2021JB021981.

McCollom, T.M. and Seewald, J.S., 2007. Abiotic synthesis of organic compounds in deep-sea hydrothermal environments. *Chemical Reviews,* 107 (2), p.382-401. cr0503660.

McCollom, T.M. and Bach, W., 2009. Thermodynamic constraints on hydrogen generation during serpentinization of ultramafic rocks. *Geochimica et Cosmochimica Acta,* 73, p.856-875.

McCollom, T.M. and Donaldson, C., 2016. Generation of hydrogen and methane during experimental low-temperature reaction of ultramafic rocks with water. *Astrobiology,* 16, p.389-406. DOI: 10.1089/ast.2015.1382.

McCollom, T.M., Klein, F., Moskowitz, B., Berquó, T.S., Bach, W., and Templeton, A.S., 2020. Hydrogen generation and iron partitioning during experimental serpentinization of an olivine-pyroxene mixture. *Geochimica et Cosmochimica Acta,* 282, p.55-75. DOI: 10.1016/j.gca.2020.05.016.

Merdith, A.S., Real, P.G., Daniel, I., Andreani, M., Wright, N.M., and Coltice, N., 2020. Pulsated global hydrogen and methane flux at mid-ocean ridges driven by Pangea's breakup.

PUBLISHED IN IJOG

Geochemistry, Geophysics, Geosystems, 21 (4), p.1-20. DOI: 10.1029/2019GC008869.

Miller, H.M., Mayhew, L.E., Ellison, E.T., Kelemen, P., Kubo, M., and Templeton, A.S., 2017. Low-temperature hydrogen production during experimental hydration of partially-serpentinized dunite. *Geochimica et Cosmochimica Acta,* 209, p.161-183. DOI: 10.1016/j.gca.2017.04.022.

Moretti, I., Baby, P., Alvarez Zapata, P., and Mendoza, R.V., 2023. Subduction and hydrogen release: the case of Bolivian altiplano. *Geosciences,* 13 (4), 109, p.1-18. DOI: 10.3390/geosciences13040109.

Myagkiy, A., Moretti, I., and Brunet, F., 2020. Space and time distribution of subsurface H_2 concentration in so-called "fairy circles": Insight from a conceptual 2-D transport model. BSGF - *Earth Sciences Bulletin,* 191, p.1-13. DOI: 10.1051/bsgf/2020010.

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

Neubeck, A., Duc, N.T., Bastviken, D., 2011. Formation of H_2 and CH_4 by weathering of olivine at temperatures between 30 and 70°C. *Geochem Trans,* 12 (6). p.1-10 DOI: 10.1186/1467-4866-12-6.

Okland, I., Huang, S., Thorseth, I.H., and Pedersen, R.B., 2014. Formation of H_2, CH4 and N-species during low-temperature experimental alteration of ultramafic rocks. *Chemical Geology,* 387, p.22-34. DOI: 10.1016/j.chemgeo.2014.08.003.

Osselin, F., Soulaine, C., Fauguerolles, C., Gaucher, E.C., Scaillet, B., and Pichavant, M., 2022. Orange hydrogen is the new green. *Nature Geoscience,* 15 (10), p.765-769.DOI: 10.1038/s41561-022-01043-9.

Pearl, J., 2009. Causal inference in statistics: An overview. *Statistics Surveys,* 3, p.96-146. DOI: 10.1214/09-SS057.

Peter, S., 1989. Petroleum formation by Fischer-Tropsch synthesis in plate tectonics. *AAPG Bulletin,* 73. DOI: 10.1306/44B4A2CB-170A-11D7-8645000102C1865D.

Prinzhofer, A., Tahara Cissé, C.S., and Diallo, A.B., 2018. Discovery of a large accumulation of natural hydrogen in Bourakebougou (Mali). *International Journal of Hydrogen Energy,* 43 (42), p.19315-19326. DOI: 10.1016/j.ijhydene.2018.08.193.

Prinzhofer, A., Moretti, I., Françolin, J., Pacheco, C., D'Agostino, A., Werly, J., 2019. Natural hydrogen continuous emission from sedimentary basins: The example of a Brazilian H_2-emitting structure. *International Journal of Hydrogen Energy,* 44 (12), p.5676-5685. DOI: 10.1016/j.ijhydene.2019.01.119.

Runge, J., Bathiany, S., Bollt, E., Camps-Valls, G., Coumou, D., Deyle, E., 2019. Inferring causation from time series in Earth system sciences. *Nature Communications,* 10, 2553. DOI: 10.1038/s41467-019-10105-3.

Rystad Energy, 2024. *The white gold rush and the pursuit of natural hydrogen.* https://www.rystadenergy.com/news/white-gold-rush-pursuit-natural-hydrogen.

Sanjaya, I., Jamal, Fatturakhman, M. Lutfi, Hermansyah, Arifin, Agus Saiful, M. Sigit, Kim, Hyeong So., 2024. Evaluating The Natural Hydrogen System in Ampana Basin, Central Sulawesi: An Implication for Natural Hydrogen Exploration in Indonesia. *Journal of Geology and Mineral Resources.* DOI: 10.33332/jgsm.geologi.v25i3.896.

Singh, H. 2025. The Emergence of Natural Hydrogen: Genesis and Current Perspectives. *Scientific Contributions Oil and Gas*, 48 (1) p.91-112. DOI: 10.29017/scog.v48i1.1691.

Speciale, P.A., Behr, W.M., Hirth, G., and Tokle, L., 2020. Rates of olivine grain growth during dynamic recrystallization and post-deformation annealing. *Journal of Geophysical Research: Solid Earth,* 125, p.1-19. DOI: 10.1029/2020JB020415.

Strauch, B., Pilz, P., Hierold, J., and Zimmer, M., 2023. Experimental simulations of hydrogen migration through potential storage rocks. *International Journal of Hydrogen*

PUBLISHED IN IJOG

Energy, 48, p.25808-25820. DOI: 10.1016/j.ijhydene.2023.03.115.

Surono, M., 2012. Tectonostratigraphy of the eastern part of Sulawesi, Indonesia, in relation to the terrane origins. *Jurnal Geologi dan Sumberdaya Mineral*, 22 (4), p.199-207 DOI: 10.33332/jgsm.geologi.v22i4.119.

Tarhan, C. and Çil, M.A., 2021. A study on hydrogen, the clean energy of the future: Hydrogen storage methods. *Journal of Energy Storage,* 40, 102676. DOI: 10.1016/j.est.2021.102676.

Tarkowski, R., 2017. Perspectives of using the geological subsurface for hydrogen storage in Poland. *International Journal of Hydrogen Energy,* 42 (1), p.347-355. DOI: 10.1016/j.ijhydene.2016.10.136.

Times of India, 2025. *The UN climate body adopts new guidelines to strengthen emission-reduction assessment of projects*. https://timesofindia.indiatimes.com/home/environment/un-climate-body-adopts-new-guidelines-to-strengthen-emission-reduction-assessment-of-projects-the-mechanism-to-help-countries-cut-emissions/articleshow/121272542.cms.

Vega, B., Ross, C.M., Frouté, L., Kim, T.W., and Kovscek, A.R., 2024. Enhanced hydrogen generation from olivine sand (Paper No. SPE-220916-MS) [Paper presentation]. *Society of Petroleum Engineers Annual Technical Conference and Exhibition, New Orleans*, LA, United States. DOI: 10.2118/220916-MS.

Vinsot, A., Appelo, C.A.J., Lundy, M., Wechner, S., Lettry, Y., Lerouge, C., 2014. In situ diffusion test of hydrogen gas in the Opalinus Clay. *Geological Society, London, Special Publications,* 400, p.563-578. DOI: 10.1144/SP400.12.

Ward, L.K., 1932a. Inflammable gases occluded in the pre-Palaeozoic rocks of South Australia. *Report Book 13/00137. South Australia Department of Mines.*

Ward, L.K., 1932 b. The search for oil-notes by the government geologist. *Mining Review,* 55, p.39-42. South Australia Department of Mines.

Ward, L.K., 1941. Report on the search for petroleum in South Australia. *Report Book 18/00135. Geological Survey South Australia.*

Watkins, J., Kaldi, J., and Watson, M., 2022. Geological storage of gas: Evaluation of seal properties for containment of carbon dioxide, methane and hydrogen. DOI: 10.2139/ssrn.4274161.

Zgonnik, V., 2020. The occurrence and geoscience of natural hydrogen: a comprehensive review. *Earth-Science Reviews,* 203, 103140. DOI: 10.1016/j.earscirev.2020.103140.

Zhang, Y.H., Jia, Z.C., Yuan, Z.M., Yang, T., Qi, Y., and Zhao, D.L., 2015. Development and Application of Hydrogen Storage. *Journal of Iron and Steel Research International,* 22 (9), p.757-770. DOI: 10.1016/s1006-706x(15)30069-8.

Zivar, D., Kumar, S., and Foroozesh, J., 2021. Underground hydrogen storage: A comprehensive review. *International Journal of Hydrogen Energy,* 46 (45), p.23436-23462. https://DOI: 10.1016/j.ijhydene.2020.08.138.

PUBLISHED IN IJOG