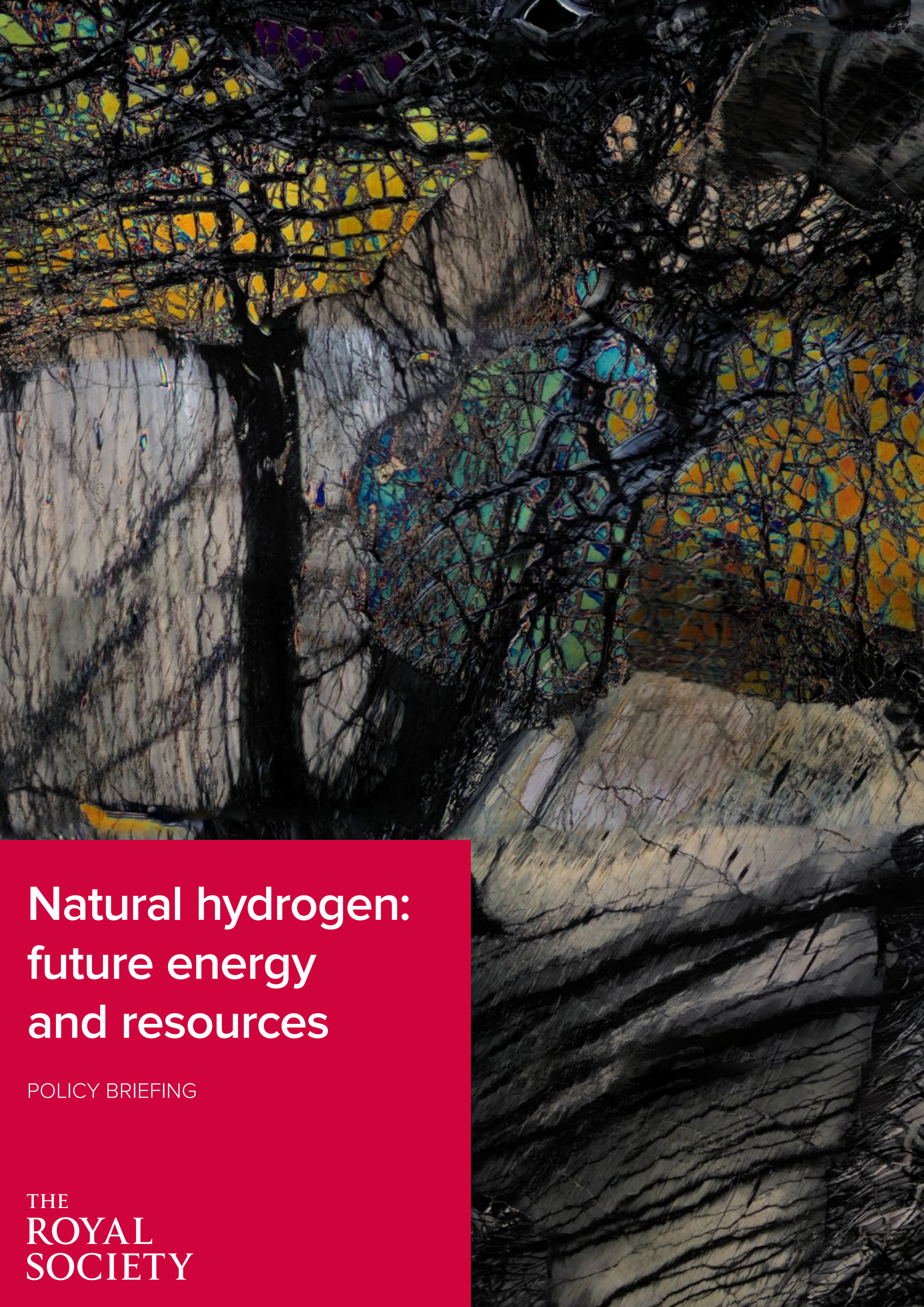

# Natural hydrogen: future energy and resources

POLICY BRIEFING

THE ROYAL SOCIETY

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**Cover image** The hydration of olivines to serpentine and magnetite results in accompanying production of hydrogen through water-rock reaction. Serpentinised mantle peridotite drilled from 1.1km beneath the Lost City Hydrothermal Field (30°N; Mid-Atlantic Ridge). Thin section image courtesy of International Ocean Discovery Program Expedition 399: Building Blocks of Life, Atlantis Massif.

# Contents

# Executive summary

## What is natural hydrogen?

Hydrogen is widely used in the petrochemical industry and in fertiliser production. It gives off no carbon dioxide when burned, making it a promising replacement for fossil fuels and a method of storing renewable energy. Traditionally made from fossil fuels (eg methane), focus has shifted to producing 'green hydrogen' from the electrolysis of water powered by renewable energy. However, this process is energy intensive and requires a rapid expansion of renewable energy capacity. Considering this, alternative hydrogen sources that do not rely on fossil fuels are gaining interest. This includes 'natural hydrogen'.

Natural hydrogen as defined in this report is hydrogen that occurs in rocks and soils in the Earth's crust produced by geochemical and biological processes, without any human involvement. In this report we focus on natural hydrogen already present as hydrogen ($H_2$), as opposed to processes of stimulation or fracking to enhance hydrogen production from rocks (sometimes called stimulated geologic hydrogen). Hydrogen has long been known in the oil, gas and mining industries, and has been extensively studied around the world through studies of the deep subsurface microbial biosphere, but in terms of energy or economic potential has generally been treated as an unwanted byproduct and/or a risk factor.

## Formation of natural hydrogen

There are two main natural mechanisms that are known to produce hydrogen:

- Serpentinisation and other chemical reactions between water and rocks rich in iron.
- Radiolysis – the splitting of water molecules by naturally occurring and safe radiation within rocks containing uranium (U), thorium (Th) or potassium (K).

The types of rock which typically could produce hydrogen are quite common worldwide. However, production and preservation depend on factors such as the geology, water availability, temperature, gas migration pathways and the absence of microbial activity that might rapidly consume hydrogen – all of which are active areas of research. The use of surface phenomenon including hydrogen seeps and soil gas concentration monitoring as an exploration tool is under development, but it is important to consider the potential for false positives (eg hydrogen production from microbes, or drilling artifacts), and false negatives (eg due to microbial consumption of hydrogen diffusing from potential commercial accumulations at depth). Although large volcanic/hydrothermal sources of hydrogen exist around the world, these areas are usually not practical for commercial extraction. Indeed, coupling hydrogen data with noble gas tracers suggests there is little evidence to date to support claims of economic long-term renewable natural hydrogen sources of volcanic/mantle origin.

## The potential for natural hydrogen as a future energy source

There is currently not enough publicly available data to give an accurate figure for the potential volumes of natural hydrogen stored in specific subsurface trapped in reservoirs, but global flux estimates have been made for decades. Reviewing recent literature suggests that, excluding volcanic gas flux (as noted, unlikely to be a commercial target), continental geological hydrogen flux can be estimated to be <0.74 million tonnes $H_2$/year. Including volcanic gas flux yields a value of <1.74 million tonnes $H_2$/year. Based on hydrogen measurements, both estimates are significantly lower than some recently proposed values based on modelling. In all cases the estimates are substantive, all the more so if such hydrogen fluxes can accumulate in subsurface traps over long geological time scales. Discoveries of such significant accumulations of natural hydrogen in the continents, in traps that are sustained by hydrogen fluxes of this magnitude, could be a game changer. Even capturing a small proportion for commercial use could enable natural hydrogen to play a significant role in the coming years.

Currently, natural hydrogen is only produced commercially at the Bourakébougou Field, a small site in Mali, which powers local energy needs. But exploration projects are currently underway around the globe, including but not limited to France, Spain, Australia, USA, Finland and Canada. The impact of these projects on local, regional or international energy markets is still uncertain and will depend on many factors such as the scale of the discovery, its location relative to potential markets and the purity of the hydrogen.

Initial targets for economic exploitation of hydrogen may be most favourable in regional concentrated industrial hubs co-located on the same geologic settings where hydrogen accumulations have most often been found (eg iron-rich or iron-magnesium rich rocks that are already the hubs for mining of gold, copper, nickel, diamonds or critical minerals). As storage/transport infrastructure for hydrogen of all forms (including green hydrogen) develop on a global scale, natural hydrogen hubs may form part of those larger networks and markets.

## UK potential for natural hydrogen

The UK has developed a hydrogen strategy and is planning to use low-carbon hydrogen to replace fossil fuels in a variety of uses. The current plans focus on the generation of green hydrogen (defined above) and blue hydrogen (from fossil fuel but coupled with carbon capture utilisation and storage; CCUS). Like many other countries around the world, the UK does have some geological areas that may have the potential to accumulate significant quantities of natural hydrogen. This includes geologic settings with hydrogen generation potential from radiolysis (including granites, mafic and ultramafic rocks) as well as serpentinisation (mafic and ultramafic rock). For the United Kingdom no databases currently exist to evaluate occurrences of natural hydrogen, and no co-ordinated nationwide exploration has taken place. Available maps to date from other countries are often empirical, and as such are inherently prone to the 'false negative' problem ie locations with no hydrogen may be because hydrogen has not been looked for; or, because hydrogen has not been analysed for (as until recently hydrogen analysis was not part of routine gas analysis and reporting). Globally much effort is focusing on producing maps of hydrogen potential moving from empirical maps of reported occurrences to more predictive maps integrating mineralogy, lithology, structural and trapping features, transport pathways, and geophysical data.

### Technologies and environmental impact of extracting natural hydrogen

It is generally understood that technology needed for natural hydrogen extraction will be similar to that for natural gas well exploration, exploitation and monitoring for leak detection, but with design adjustments for hydrogen's unique properties. Extraction could involve drilling several deep production wells into the geological formation trapping the hydrogen, followed by purification and storage on the surface.

Natural hydrogen is often found co-located with other substances including methane ($CH_4$), carbon dioxide ($CO_2$), helium (He), nitrogen ($N_2$) and lithium (Li). While helium and lithium can make natural hydrogen extraction more commercially viable, other impurities such as carbon dioxide and methane might increase costs due to the need for separation and disposal.

Whilst natural hydrogen itself poses no more environmental hazards than hydrogen produced by other methods, its extraction will have different impacts on the environment, both above and below ground. Care will need to be taken to keep hydrogen leakage to a minimum and the impact of hydrogen exploration and exploitation on subsurface microbiology is not well constrained. Although hydrogen can have indirect greenhouse effects, its impact on global warming is lower than that of methane, especially in terms of short-term climate effects. Although many factors are still uncertain, it is likely that the overall carbon emissions of a high-purity source of natural hydrogen will be similar to or less than that of green hydrogen powered by renewable energy.

### Cost to produce natural hydrogen

Value chains and life cycle analyses for natural hydrogen are still nascent – in part because of major remaining questions about the accessibility, distribution and scale of potential natural hydrogen use. The cost of natural hydrogen remains to be determined, as it has not been produced or sold in large quantities. Costs will depend upon several factors including scale of extraction, location and source purity. Natural hydrogen cost estimates are most typically directly compared against green hydrogen. While natural hydrogen would require energy and material inputs to extract, purify, transport and in some cases, store, the overall energy requirements for the entire life cycle may be significantly reduced in comparison to green hydrogen which is largely dependent on electricity sources used for processing. Another important factor in the cost is where the natural hydrogen is produced in relation to end-users. If other energy sources are expensive due to transport difficulties, or, in aid of decarbonisation, a local natural hydrogen source might be an attractive low carbon alternative. Overall natural hydrogen has the potential to diversify the global hydrogen supply.

## Conclusions

1. Natural hydrogen is produced and accumulates underground by natural processes that can be accessed using established drilling methods and could be of economic potential if accumulated and stored in sufficient size reservoirs.

2. There are many locations around the world that have the potential for natural hydrogen, but more research and exploration is needed to determine the extent and location of commercially viable fields (eg purity of hydrogen, volume, depth and accessibility).

3. Initial targets for economic exploitation of hydrogen may be most favourable in regional concentrated industrial hubs co-located on the same geologic settings where hydrogen accumulations have most often been found (eg iron-rich or iron-magnesium rich rocks that are already hubs for mining of gold, copper, nickel, diamonds or critical minerals).

4. The carbon emissions of natural hydrogen exploitation are likely to be similar to or lower than green hydrogen.

5. The true cost of natural hydrogen remains to be proven, as it has yet to be produced and sold in quantity. Given a large enough reservoir of high purity hydrogen with easy access, published cost estimates suggest that natural hydrogen could be competitive with other colours of hydrogen.

6. The UK currently lacks enough data and knowledge to conclude if it has significant natural hydrogen deposits. But as it has geologic settings with at least theoretical hydrogen producing potential, the UK can benefit and contribute to global momentum to understand and map hydrogen potential and prospects.

7. Published data does not support the likely existence of an endless supply of natural hydrogen transiting from deep mantle sources and accumulating in accessible near surface reservoirs amenable for economic exploitation.

# Introduction

Across the globe, the demand for energy grows year by year. In 2023, demand grew by 2% reaching 172,200 TWh. The US Energy Information Administration forecasts that energy demand will grow by 50% to 2050[1]. Most of the world's energy comes from combusting fossil fuels (coal, oil and natural gas) resulting in the liberation of carbon dioxide ($CO_2$). 2023 set a record with the annual emission of $CO_2$e (carbon dioxide equivalent) exceeding 40 GT, of which about 87% came from the use of fossil fuels[2].

Reducing the dependency humans have on fossil fuels is difficult, most notably due to the high energy density. Combusting coal liberates far more energy than burning an equivalent mass of wood, abstracting heat from hot water, or generating electricity from wind or solar panels. Coal, oil and gas are easy to store and transport when compared with energy derived by renewable sources, which require significant developments and upscaling in storage technologies. However, the use of renewable energy is significantly growing across the globe. In 2022, the total quantity of renewable energy used was 8,988 TWh, a five-fold increase on 1980[3], which constitutes a little over 5% of global energy demand. Clearly not enough is currently being produced to replace fossil fuels in a meaningful way, nor is the rate of investment and energy transition keeping pace with the continued rise in $CO_2$ emissions.

Of the energy sources available to society today, only nuclear fission and hydrogen are more energy dense than fossil fuels. Hydrogen[4] has the potential to reduce fossil fuel use, especially natural gas (methane, $CH_4$). It has about three times the gravimetric energy density (kWh/kg) of natural gas, albeit with a very low volumetric density (kWh/$m^3$), due to its low molecular weight and gaseous state at ambient conditions. This means that the volume of hydrogen required is about double that of methane to deliver the same energy output from combustion. When hydrogen burns, it does not produce carbon dioxide. Under lean burn combustion, hydrogen only produces water vapour ($H_2O$). Hydrogen can be extracted from natural gas, or indeed any hydrocarbons (grey, black and blue hydrogen), and from water (green hydrogen), but the energy required to liberate hydrogen from these compounds is considerable and greater than that produced when liberated hydrogen is subsequently combusted (see Box 1 for definitions). In addition, for almost all the hydrogen produced from fossil fuels today, carbon dioxide is produced as an unwanted by-product.

## Hydrogen use

Today, hydrogen is used globally in metal refining, fertiliser production and hydrogenation. It is typically generated at the same site at which it is used, usually as 'grey hydrogen', produced from coal or methane (see Box 1 for definitions). Hydrogen production from fossil fuels contributes about 2% of global emitted carbon dioxide (> 800 million tonnes[5]). Hydrogen poses many promising applications, which have the potential to reduce not only UK but global carbon emissions, including but not limited to use[6]:

- as an energy vector for renewable energy storage;
- in hard-to-decarbonise industries such as steel and cement manufacturing; and
- in the chemicals industry for the manufacture of ammonia and plastics.

Although these applications show real promise, there remain many unknowns in terms of societal and environmental considerations, as well as economic and technical uncertainties, which may prevent their implementation. Demand for hydrogen has seen a 3% year-on-year growth over the past few years[7]. In a 'net-zero emissions by 2050' scenario, annual demand is expected to be around 150 million tonnes by 2030[7]. The cost of hydrogen is linked to the way in which it is manufactured.

Despite this growing interest and market for hydrogen, caution should be exhibited when considering the environmental impacts of current production methods, particularly when considered at the scale which would be needed to provide the substantial societal shifts needed to meet global net-zero targets. The most common 'colours' for hydrogen by production method are shown in Box 1.

BOX 1

## The hydrogen rainbow: hydrogen generation type definitions

Hydrogen is commonly referred to in a colour-coded naming system which describes the production process of that hydrogen. However, with increasing numbers of generation types, the rainbow of hydrogen has expanded greatly leading to confusion particularly when it comes to the subtle differences in these production processes. To that end this report will avoid, to the extent possible, the use of 'colour-coded' definitions. Specifically, for the key topic of this report, the term natural hydrogen will be used rather than terms such as white hydrogen (described below). Natural hydrogen refers to hydrogen which is naturally occurring in the Earth's crust and generated by naturally occurring geochemical reactions with no human involvement in its initial production in the crust.

This distinguishes the topic of this report, natural hydrogen, from the term 'geologic hydrogen' which is sometimes used interchangeably with natural hydrogen, but in other cases refers specifically to 'stimulated geologic hydrogen', referring to geo-engineered or stimulated processes whereby subsurface hydrogen production is enhanced by fracking and/or fluid injection techniques.

The most commonly discussed generation types are described below. Throughout this report, wherever the term 'hydrogen' alone is used, this refers to natural hydrogen only.

**Grey hydrogen** is generated through steam reformation of natural gas or methane without the capture of the resulting co-generated greenhouse gases such as $CO_2$.

**White hydrogen**, is sometimes used to refer to natural hydrogen, as defined above.

**Blue hydrogen**, similar to Grey, is generated through steam reformation of natural gas or methane, except co-generated greenhouse gases are captured and stored. Therefore, it is often referred to as a lower-carbon option for hydrogen generation (assuming renewable process energy input).

**Green hydrogen** is generated from the electrolysis of water using electricity from renewable sources, typically wind and solar.

**Pink hydrogen** similar to Green is generated through electrolysis of water. However, it differs as this is powered by nuclear energy as opposed to renewable energy.

**Turquoise hydrogen** is generated from pyrolysis of natural gas or methane resulting in the carbon by-product being in a solid synthetic graphite form which can then be used in industry.

**Gold hydrogen** is generated from depleted oil wells being pumped with mixes of nutrients and bacteria to convert the residual oil into hydrogen and $CO_2$. This generation type does not directly refer to any capturing or storing of the resulting $CO_2$ by-product.

**Orange hydrogen** (sometimes also referred to as stimulated geologic hydrogen) is generated by the injection of iron-rich geological formations with water and $CO_2$ and other chemicals which react with the iron producing hydrogen which can be extracted while the $CO_2$ is sequestered.

**Black and Brown hydrogen** is generated by the gasification of black and brown coal respectively. This process generates not only hydrogen but also $CO_2$.

## Natural hydrogen

Natural hydrogen occurs as molecular hydrogen ($H_2$) and is not compounded with another element. It exists in the Earth's atmosphere at a very low concentration and in slightly higher concentrations dissolved in water ($H_2O$). Hydrogen also occurs naturally as a gas phase within porous rocks in the subsurface where it has been found in near pure form at the Bourakébougou field in Mali[8] but more commonly elsewhere mixed with other gases, typically nitrogen ($N_2$), helium (He) and methane ($CH_4$), or dissolved in groundwaters (Figure 1).

### Co-associated gas compositions of hydrogen systems

The Bourakébougou hydrogen gas field has a gas composition of 97.4% hydrogen ($H_2$), 1.2% nitrogen ($N_2$) with trace amounts (<0.05%) helium (He), carbon dioxide ($CO_2$) and methane ($CH_4$)[8]. Hydrogen bearing gases are more usually mixed with $CH_4$ and $N_2$ in varying proportions, sometimes containing significant (>0.5%) He. For example, gases from the hyperalkaline springs in the Oman Samail ophiolite contain ~70 – 90% hydrogen, with the co-associated gas dominated by $N_2$ and smaller amounts of $CH_4$[9]. Hydrogen-rich gases in Kansas have been reported to contain between 40 – 60% hydrogen, with the co-associated gas from exploration wells penetrating the basement to be initially dominated by $N_2$ and some He[10]. In contrast to $N_2$ dominated co-occurring gases, gas seeps from the Chimera ophiolite, Turkey, contain only ~10% hydrogen, with the co-gas dominated by $CH_4$[11]. Hydrogen-rich gases reported from underground fracture fluids and groundwaters similarly have co-gases dominated by either $N_2$ or $CH_4$ or both with typically high (percent) levels of associated helium[12].

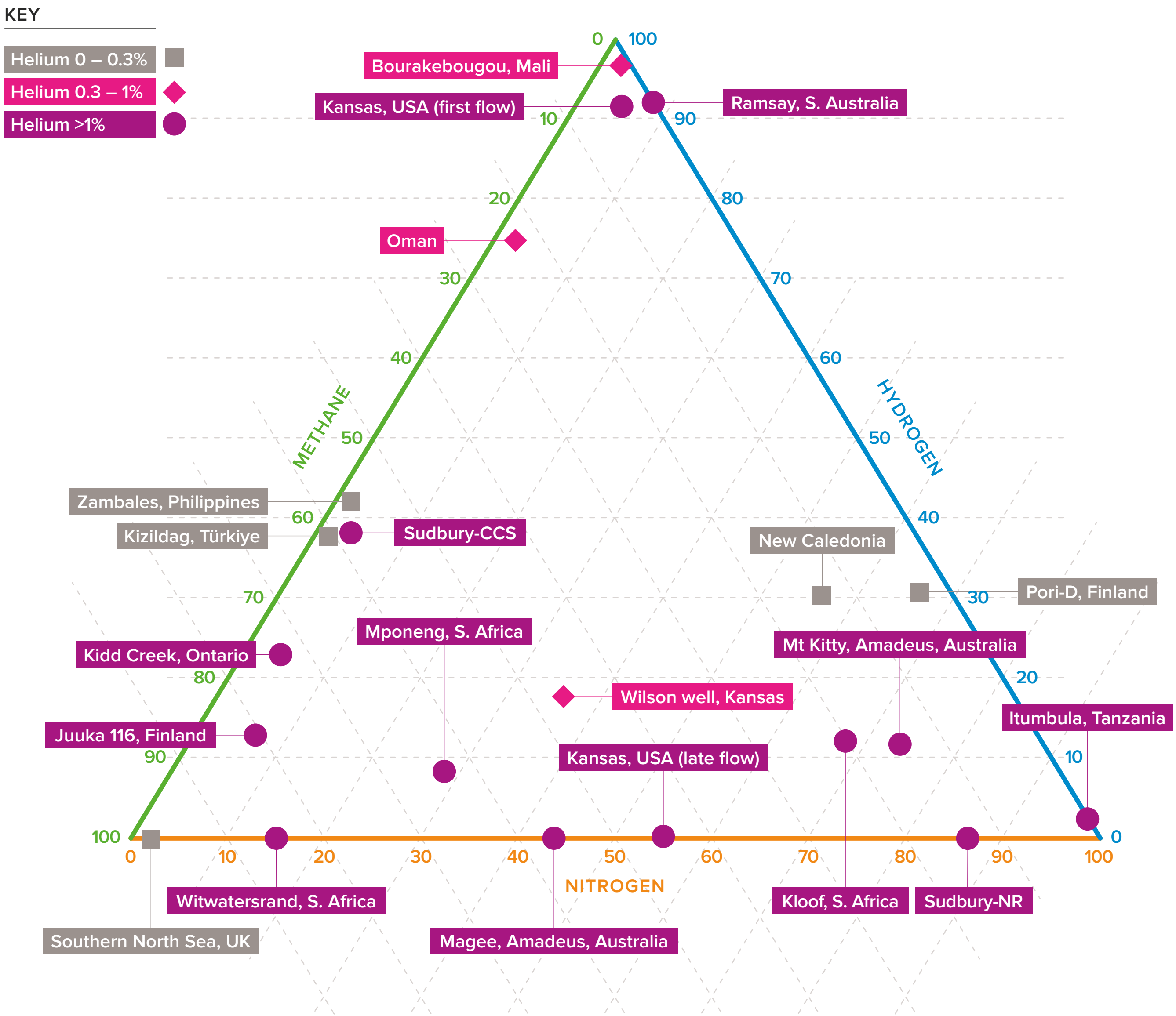
Dilution by $CH_4$ and $N_2$ co-gases can result in very low hydrogen concentrations that will provide the limit for commercial viability. While this will depend on many factors, low hydrogen concentrations may be compensated by the value of co-produced He and $CH_4$. Greenhouse gas emissions are dominated by the hydrogen to methane ratio of the produced gas. A case with 85% hydrogen, 12% $N_2$, and 1.5% $CH_4$ emits about 0.4 kg $CO_2$ equiv/kg hydrogen. This compares with a gas containing 75% hydrogen and 22.5% $CH_4$ which emits 1.5 kg $CO_2$ equiv/kg hydrogen[13]. Blue hydrogen (ie with carbon capture and storage) emits 8.9 kg $CO_2$ equiv/kg hydrogen[14] and solar-photovoltaic (PV)-derived hydrogen of 3.6 kg $CO_2$/kg hydrogen[15].

The existence of natural hydrogen has been known for some time[16, 17, 18]. Indeed Ward (1933)[19] reported on a well drilled on Kangaroo Island offshore Adelaide, South Australia in 1921. Hydrogen concentrations of between 50% and 70% were recorded from the gases sampled.

Despite the ample evidence that molecular hydrogen occurs both as a seeping gas and trapped underground in either gas phase or dissolved in groundwaters as indicated by these figures, it has only over the past decade come to the focused attention of the energy industry (and hence to policy makers, regulators and society) to systematically explore for subsurface natural hydrogen as a primary energy resource.

FIGURE 1

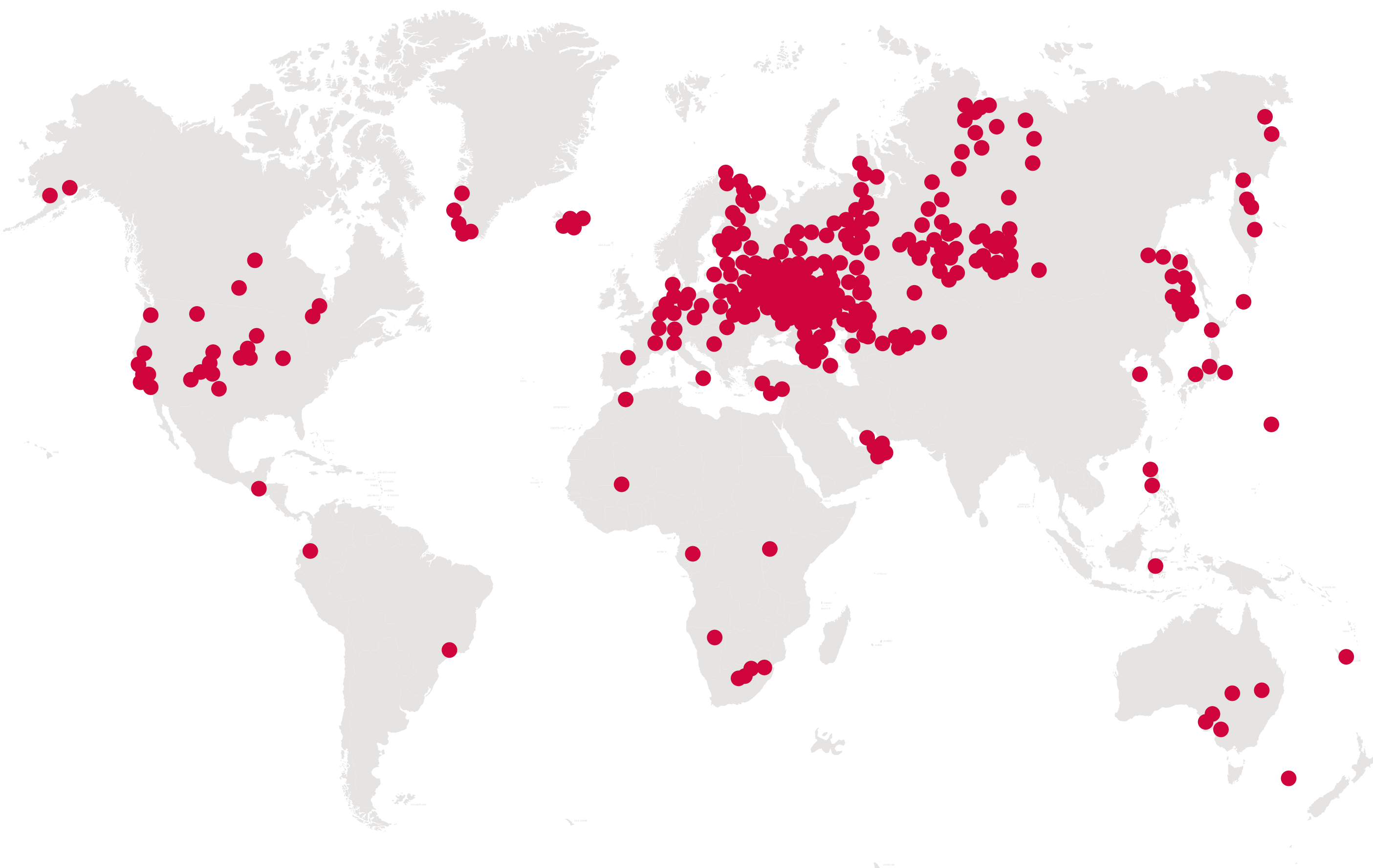
Hydrogen, nitrogen, methane ternary plot for gases.




Source: Data from Gluyas *et al* 2025[20] and references therein.

FIGURE 2A

Published occurrences of primarily free gas hydrogen including some aquifers and fluid inclusion data, all those with > 10% hydrogen.

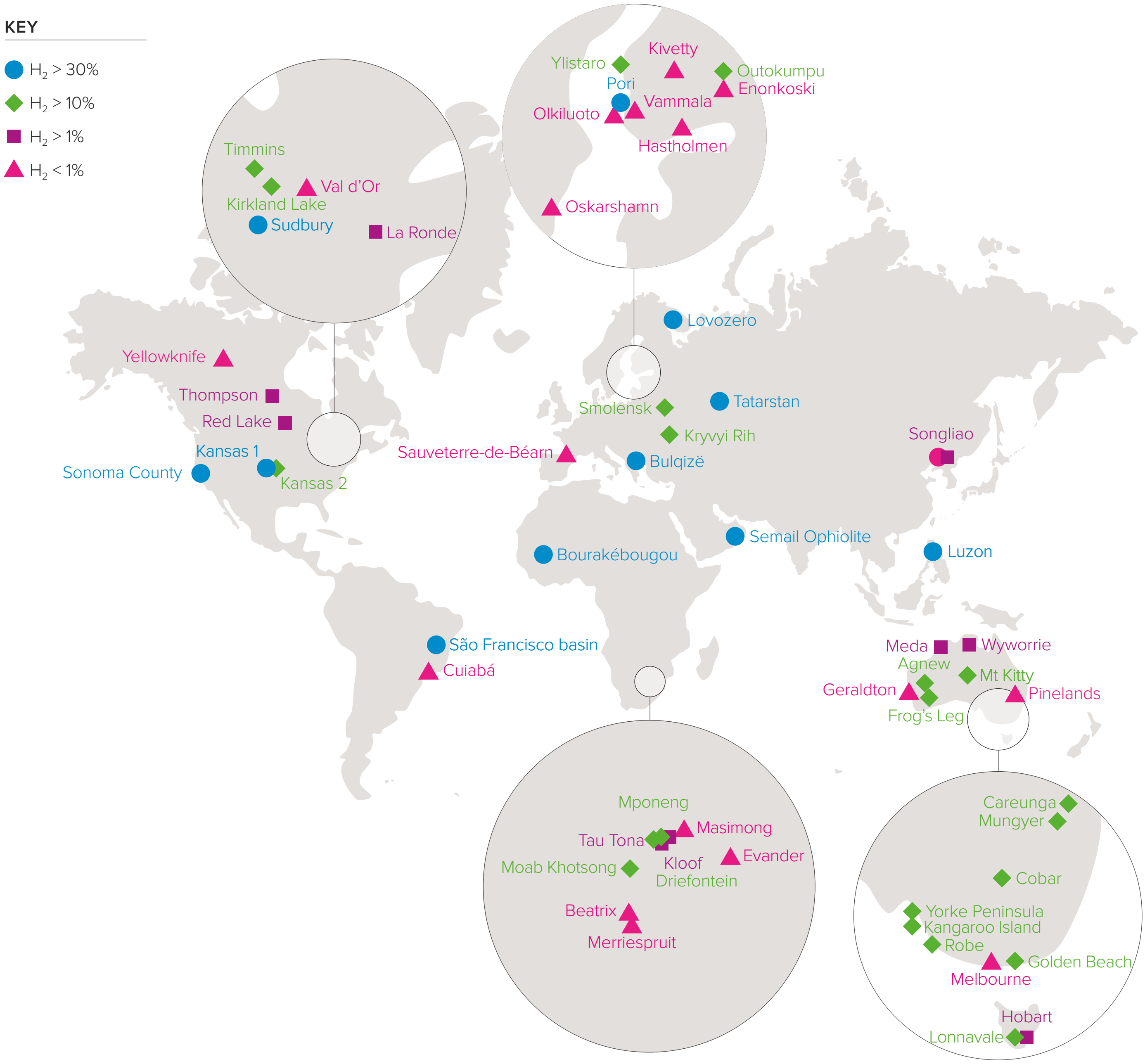


Source: Oxford Institute of Energy Studies. OIES[21], 2024 and adapted from Zgonnik, 2020[22].

## FIGURE 2B

Locations and published concentrations (expressed as % of exsolved gas phase) for hydrogen found in the continental crust.

Dots represent the highest reported hydrogen percentage reported at each location. Where several wells or occurrences are in a single site, a single dot is shown to reflect the region. Hence the dots represent multiple occurrences in most cases. Measurements that showed no hydrogen are not reported here but can be found in the original publications. Additional data since 2014 now included from China[23], Australia[24], Albania[25], Mali[8], Moab Khotsong, South Africa[26], Laronde, Canada[27], Kirkland Lake, Canada[28], from Brazil[29, 30] and France Pyrenees[31].




Source: Figure updated and adapted from Sherwood Lollar *et al.* 2014[32] and references therein.

### Volumes and locations of natural hydrogen

The locations and volumes of natural hydrogen occurrences around the world are not known and are highly uncertain. That said, natural hydrogen generation globally has been estimated at around 0.1 – 0.5 million tonnes per year in the Precambrian continental crust[12, 32]. Recent papers have published global estimates in the range of 20 million tonnes per year[22, 33, 34] (see Box 2). Capturing even a small proportion of this for energy based on any of these estimates could be worthwhile commercially. To refine and develop estimates relevant to a particular locality, progress must be made in:

- understanding the production mechanisms;
- the expulsion efficiency of hydrogen from source rocks;
- the proportion which has migrated through rocks and become trapped;
- how long the traps have retained their integrity; and
- the possible loss of hydrogen to microbial sinks or abiotic/geologic sinks through chemical reactions[35, 36].

To date, there is only one natural hydrogen field in production, Bourakébougou, Mali, although Helios Aragon's Monzón Field in northern Spain has progressed to planned production. The Bourakébougou Field was discovered by accident in 1987 while drilling for water, and a further 24 wells have been completed since 2017 with some as shallow as 100 m below surface[37]. The reservoir rock is carbonate and intruded igneous rock is suggested to act as the seal. The one deep well penetrates to basement rock, and it is reported, though unverified, to have additional deeper reservoirs. Hydrogen flow rate from the 1987 discovery well was reported as 1,500 $m^3$/day. The rate is exceptionally modest, compared, for example, with a high-quality production well from a conventional gas reservoir in the North Sea at more than 2 million $m^3$/d[38]. Maiga *et al*[37] suggested that no pressure decline had been seen in the field despite production of hydrogen. They interpreted this to indicate that hydrogen is being continuously produced elsewhere to replace that extracted. This is speculative as on-going rates of hydrogen production from radiolysis and serpentinisation are slow[32] (see below) and both the low production rate and the possibility of the tapped interval being fed from a deeper accumulation could also result in zero to negligible pressure decline. Reserves figures have not been published for Bourakébougou. Indeed, there are no resource or reserve figures[39] for the Earth for current projects or discoveries listed by International Energy Agency (IEA)[40] shown in Table 1.

TABLE 1

List of current hydrogen exploration projects and reported hydrogen discoveries at the time of compilation (modified from IEA, 2024[40] and OIES, 2024[21]).

| | Country | Location | Status/comments |
|---|---|---|---|
| **Africa** | Mali | Bourakébougou | 25 positive exploration wells (since 1987, 98% hydrogen at approximately 4 bars). Economic assessment in progress. |
| | South Africa | Northwest, Gauteng, Limpopo, and Mpumalanga provinces | H2Au Limited obtained three exclusive exploration permits spanning a total of 15,000km2 in November 2024. |
| | Tanzania | Rukwa | Noble Helium's Rukwa acreage Mbelele well reported 2.24% helium and hydrogen levels 1,500 times that of background (Tanzania Invest, 2024). Planned shallow geophysics planed for Aug 2024. |
| **Europe** | Albania | Dibër County | Largest known natural hydrogen flow at Bulqizë Mine, up to 84% hydrogen (OIES21, 2024) |
| | Finland | Outokumpu Belt | Launching an exploration and sampling programme, building on work by the Geological Survey of Finland. Hydrogen concentration as high as 46%, 2024. |
| | France | Pyrénées-Atlantiques | 'Sauve Terre H[2]' – Application for exclusive exploration licence (225 $km^2$) submitted in July 2022. First licence for natural hydrogen granted in France in November 2023. |
| | France | Pyrénées-Atlantiques | 'Grand Rieu' – Application for exclusive exploration license (266 $km^2$) submitted in March 2023. Award granted in March 2025. |
| | France | Pyrénées-Atlantiques | 'Coucourou' – Application for exclusive exploration licence submitted in April 2024 (523 $km^2$). Award expected Q4 – 2025. |
| | France | Landes | 'Marensin' – Application for exclusive exploration license (691 $km^2$) submitted in April 2023. Award granted in March 2025. |
| | France | Lorraine Basin | 'Trois Evéchés' – Application for exclusive exploration licence submitted in September 2023 (2,254 $km^2$), award expected in 2025. |
| | France | Lorraine Basin | 'Regulator 2' – Research partnership between scientists and industry to estimate feasibilities of coal bed methane exploration 2018. Received USD 1.3 million from the European Union. |

| | Country | Location | Status/comments |
|---|---|---|---|
| **Europe** | France | Hautes-Pyrénées / Haute Garonne | 'Comminges' – Application for exclusive exploration license submitted in May 2024 (758 – 759 km²). Award expected Q4 – 2025 / Q1 – 2026. |
| | Kosovo | Dinarides | 'Banja Vuca' – Application for exclusive exploration license (57 $km^2$) submitted in January 2023. Award expected in 2025 – 2026. |
| | Spain | Huesca Province | Project received government approval 2022. Monzón Field (reported at 99% hydrogen with associated helium (OIES, 2024). First well drilled and production to commence from Jan 2029. |
| **Oceania** | Australia | Eyre Peninsula | H2EX PEL granted PEL June 2022 and received USD 570,000 grant from federal government to develop natural hydrogen licence. |
| | Australia | Amadeus Basin | A Farm-In Agreement was established with Greenvale by funding seismic and drilling activities (Oct 2023). 2D seismic in progress. Drilling planned for August 2025. |
| **Middle East** | Oman | Semail Knappe | Ministry of Energy & Minerals signed a Memorandum of Understanding (MoU) in September 2023 to assess the potential of geologic hydrogen exploration in Oman. Eden GeoPower US DOE funded to determine production potential in 2024. |
| **North America** | Canada | Northern Ontario | Drilling planned for mid-2024 near Timmins and Sudbury in Northern Ontario. Millbank Mining acquires Blakelock Natural Hydrogen project. (22 $km^2$, Sep 2024). |
| | Canada | Saskatchewan | Exploring Rider Natural Hydrogen Project (3,356 $km^2$), with historical grades up to 96.4% reported (Max Power, 2024). Approaching drill ready stage Q1 2025. |
| | USA | Kansas | HyTerra hold exploration leases in Kansas (51 $km^2$), USD 4 million fundraised. Plans to continue leasing high priority acreage and drill two exploration wells. Geneva project drilled exploration hole in 2023 results to be determined. |
| | USA | Global | Hydrogen start-up Koloma has raised USD 336 million through two fundraisers. Drilling expected by the end of 2024. |
| **South America** | Brazil | State of Bahia | Petrobras investing USD 3.8 million R&D investment on the generation and viability of extracting natural hydrogen within Brazil. The operation began in October 2023. |

Over the past decade various empirical maps of natural hydrogen occurrences have appeared via academic literature. These range from a focus on subsurface accumulations[23], to surface discharges or seeps[22, 41], and reviews or regional studies applying various criteria to evaluate the occurrences in the context of commercial potential and/or identification of areas for additional exploration[22, 24, 16]. A recent series of papers are developing protocols and best practice recommendations for identifying hydrogen surface observations related to artifacts of microbiology and or/drilling[10, 24, 42, 43].

With rising interest in the potential commercial viability of natural hydrogen in the energy transition, national mapping projects led by geological surveys and others are underway to produce more detailed assessments and maps that might guide hydrogen exploration. Typically, these are based on evaluation of at least one of three types of input:

- potential source rock types;
- potential structural features providing possible migration pathways; and
- and to some degree, an estimation of potential reservoir rocks.

Some of these efforts also integrate reported hydrogen occurrences (or other proxy data such as helium), but to date such data are mainly drawn from previously published academic literature, as reporting of hydrogen content in samples is not common in many countries. Where possible, national mapping efforts are integrating drill testing data from various agencies including private and public exploration wells and groundwater wells, among others[44, 45, 46,] while recognising the absence of hydrogen being reported may be a false negative as this analysis is not a routine analyte in most of this activity. Furthermore, data only exist in areas where it has been looked for. Most datasets and maps are inherently empirical in that sense and may under-report the distribution and occurrences of hydrogen.

Notable examples of national mapping efforts include the US Geological Survey's (USGS) program to produce a hydrogen prospectivity map based on geologic inferences and weighting of prospectivity based on proxy data sets[33, 34]. It is important to note the report to date does not include hydrogen measurements or reported hydrogen data, and assumes widespread regional vertical and lateral migration across the continental US on the scale of hundreds of km. The utility of the maps will depend on verification of these and other assumptions.

The Geological Survey of Canada's work is based on similar approaches, in particular exploration for both hydrogen and helium[46], and mapping efforts in the provinces of Quebec[44] and Manitoba[45]. Other efforts are pending from the GTK (Geological Survey of Finland) and IEA (International Energy Agency), among others. By focusing on source rock potential, and in some cases modelling estimates examining different scales of possible hydrogen resource exploitation and development[46], these efforts hope to fill some of the gaps inherent in the empirical maps of hydrogen occurrence commonly cited to date[22, 32, 21].

### UK natural hydrogen – knowledge, activity and opportunities

The UK's Hydrogen Strategy[47], introduced in 2021, highlighted that low carbon hydrogen will be essential for the UK to achieve net-zero, and meet the UK's Sixth Carbon Budget target[48]. This anticipated that hydrogen will make up between 20 – 35% of UK final energy consumption by 2050. In 2022 the UK government doubled its ambition, pledging to deliver up to 10GW of low carbon hydrogen production capacity by 2030[49], positioning hydrogen as a central component of its transition to a cleaner, more secure energy system.

To date, there has been no comprehensive UK wide assessment of natural hydrogen potential. While the British Geological Survey (BGS) and Mine Remediation Authority (MRA) cover related subjects, neither has carried out a country-wide view of its possible occurrence. However, their ongoing activities could offer a strong foundation from which to expand the knowledge of hydrogen as a possible UK resource. At the time of writing, BGS has been commissioned to assess the geological potential for natural hydrogen in the UK based on existing literature and the most representative hydrogen production mechanisms. The resultant report will focus on identifying the processes of hydrogen generation, migration and accumulation ('plays') across the British Isles offering a basis for further research and exploration. The mapping and mineral investigation of granite rocks that contain uranium, thorium and potassium as well as mafic and ultramafic rocks that, through hydration reactions such as serpentinisation, could also produce hydrogen, also falls under the remit of the BGS.

No other public/commercial body or UK university is known to be conducting national-scale research into the possibility of UK natural hydrogen resources. The limited available data reflects historical exploration and regulation trends. Despite the extensive onshore and coastal drilling for petroleum and metals over the last century, there are few regulatory requirements for routine hydrogen monitoring in environmental contexts. While not directly assessing the production or presence of natural hydrogen, the environmental monitoring that The Mine Remediation Authority carries out at multiple sites across the UK's (now decommissioned) coal fields might be able to provide useful information. Historical gas surveys linked to the UK's Nuclear Waste Services might hold legacy data collected as part of Nirex investigations, although, the current Geological Disposal Facility programme does not include gas measurements.

The UK's complex geological history has resulted in a wide range of geological settings, a few of which may be conducive to the generation of natural hydrogen in the subsurface (Figure 3). Except for the coal industry, where hydrogen has been reported, the processes of hydrogen generation, migration and accumulation remain largely unstudied, whether for economic potential or for investigations of subsurface microbiology.

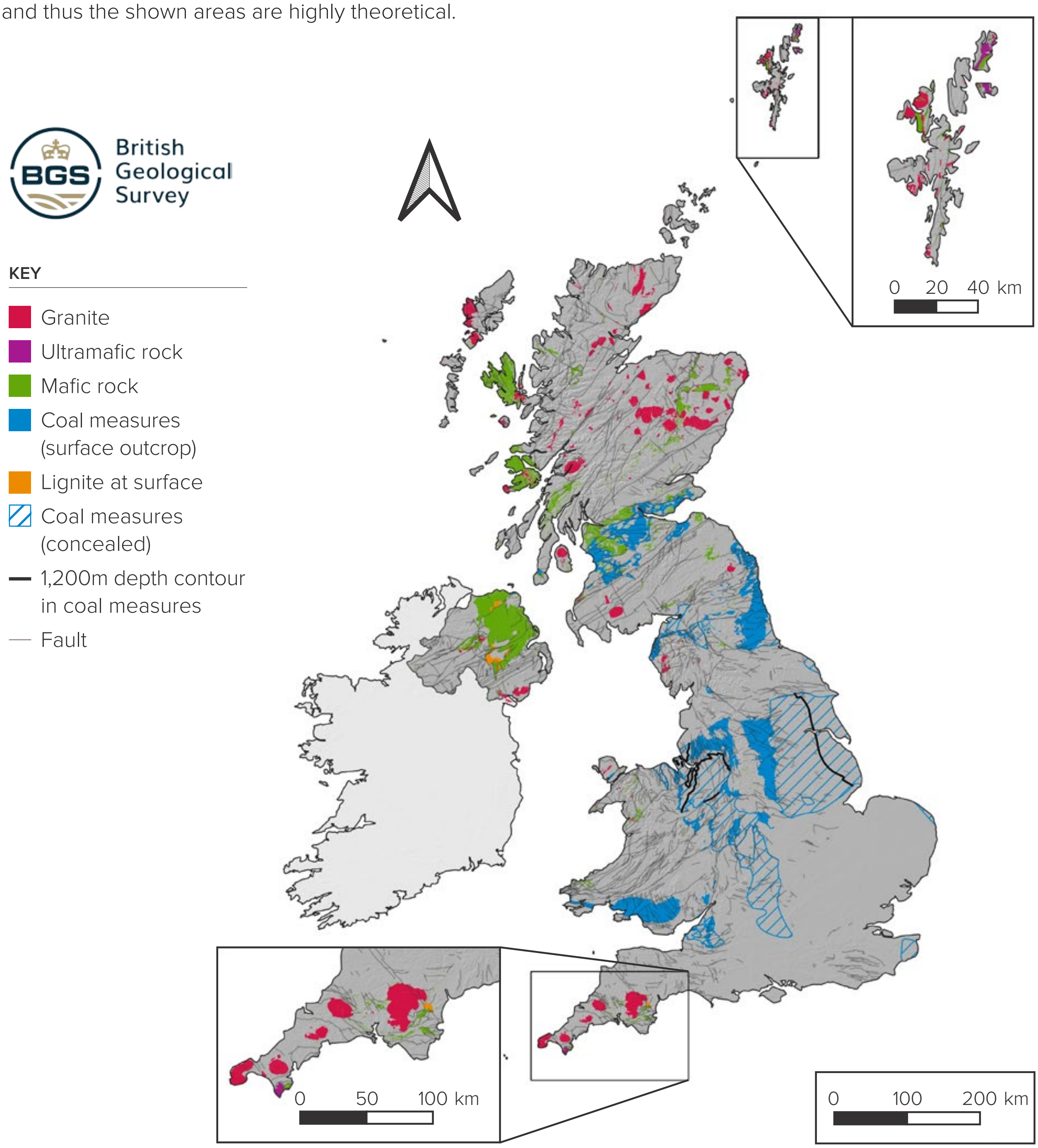
Examples of the potential source systems are presented in Figure 3 and include: the Archean mafic-ultramafic bodies within the Lewisian Gneiss Complex of Scotland, Palaeozoic ophiolites (eg Lizard Peninsula in England or Ballantrae and Shetland in Scotland), granitic plutons (eg the North Pennine Batholith or the Northeast Grampian Basic Suite in Northeast Scotland), the Upper Carboniferous Coal Measures (Pennine Coal Measure Group) or the Tertiary Igneous Province of Scotland and Northern Ireland. The UK's Paleozoic and Mesozoic sedimentary basins could serve as reservoir targets for hydrogen. However, the genetic processes, subsurface architecture enabling/inhibiting flow and accumulation and the multiscale spatial interplay of these play components have not been studied with this in mind.

The BGS's National Geoscience Data Centre (NGDC) holds vast geoscience databases of information both onshore and offshore of the UK, most of which remains largely unpublished or not assessed for hydrogen exploration suitability. There include digital lithological descriptions, geophysical, geochemical and mineralogical analyses, as well as near-surface gas data. This absence of data does not necessarily indicate that hydrogen is absent from natural gas in the UK, rather that it was not measured in many cases.

FIGURE 3

Distribution of potential geological sources of natural hydrogen in the UK onshore subsurface, including inorganic (granite, mafic and ultramafic rocks) and organic (coal measures) lithologies.

No filtering or ranking of the sources or any data investigation to indicate research and exploration targets has been undertaken, and thus the shown areas are highly theoretical.



# Context and mechanisms for natural hydrogen generation

## 1.1 Natural hydrogen: surface occurrences

The viability of natural hydrogen as a future resource hinges on accessing accumulations of hydrogen, likely in gas form, at concentrations that allow for economically viable separation from co-occurring gases, while minimising hydrocarbon content, such as methane. The distribution of known hydrogen seepage to date is shown in Figure 2a. An important finding is that these maps, and hydrogen data worldwide overall, are empirical in nature and it is important not to assume that hydrogen occurs only where it is currently reported. Areas where no reports have been published may be because no investigations have taken place, or because data may not have been made available. Hence published maps of hydrogen, whether as surface seeps or as subsurface accumulations (Figure 2b), reflect a minimum knowledge. For instance, the relatively high number of hydrogen occurrences in Eastern Europe and Asia is a result of countries actively searching for hydrogen during the Soviet era, rather than a tendency for this geographic area to be anomalously enriched in hydrogen[22]. In addition, some of the basins being explored today are without reported hydrogen concentrations. In these basins, the tectonic setting or the presence of a hydrogen proxy such as helium may be seen as the likely indicator of hydrogen potential.

Many other basins, such as those in the United Kingdom, where no significant hydrogen seepage is recorded, may still have material hydrogen potential. The first stage of detecting that possibility is a thorough testing for hydrogen in springs and other seeps that exhibit deep crustal fluid sources, (eg saline fluids and gases) or targeting of appropriate lithologies that are known to produce hydrogen. At the time of writing, no such study in the UK is known.

## 1.2 Natural hydrogen systems: source to accumulation

The natural hydrogen occurrences in Figures 2a and 2b are the product of a complex system comprising multiple sources of hydrogen. So-called 'volcanic' or 'magmatic' hydrogen from the Earth's mantle is a significant component of planetary hydrogen, including discharges at the surface in volcanic zones and hot springs. Reduced gases such as methane from the mantle as a supposed commercial resource received considerable attention and controversy in the 1980s, but such claims were disproved by demonstrating the absence of any mantle input associated with these systems by applying noble gas geochemistry[50, 51]. Similarly, hydrogen found in most crystalline rock settings have to date been shown to not be mantle-derived[32]. The majority of sites globally under investigation for hydrogen economic potential lie in crustal rocks for which no mantle-sourced component has been identified (via noble gases' isotope chemistry); or for which the tectonic setting makes such a component geologically implausible.

Helium is a particularly important tool. Helium is co-produced with hydrogen in many crystalline settings via radiolysis processes[32] and shares similar physical characteristics with hydrogen, such as its diffusivity and solubility in water[52, 53]. As a noble gas, helium is unreactive and provides a conservative tracer of source rock and migration processes. Along with the other noble gases, it is a direct test of the contribution of any mantle-derived input and can quantitatively resolve inputs from the mantle, radiogenic crust, and atmosphere. It can also provide insight into either preservation of hydrogen, or loss of hydrogen to chemical or biological sinks[36, 54, 12.] Potential hydrogen sinks will be addressed in Section 2.2.

The two most common and volumetrically important hydrogen sources are (see Figure 4):

- the hydration of iron rich minerals (through a series of reactions broadly referred to as 'serpentinisation') or oxidation of iron-rich minerals; and
- the radiation driven cracking of water molecules ('radiolysis').

Understanding the kinetics, rates and optimal conditions for both processes are areas of active research (see reviews by Ballentine *et al*[55] and Gluyas *et al*[20]). While serpentinisation reactions may produce peak levels of hydrogen at higher temperatures (200 – 320°C), many recent studies have demonstrated that the range of mineralogy, pH and temperature favourable to hydrogen production is much wider than previously understood[56, 57, 58, 59, 60, 61]. Self-propagating reactions may be sustained by the volume expansion associated with serpentinisation that result in increased factures and surface area as the reactions proceed[32, 62, 63]. During radiolysis having water close to the distributed radioelements in the host rock optimises hydrogen production and as such smaller grain sizes and higher water-rock ratios[12, 64, 65, 66] are favourable. Hydrogen production from kerogen, coal and hydrocarbons has also been suggested, as well as fracture-induced hydrogen production in fault zones[67, 68]. To date there is no evidence that these are volumetrically significant although research in both areas continues.

## FIGURE 4

Main categories of chemical water-rock reaction producing hydrogen – as well as other key elements including dissolved sulphate[69].

**1) Redox reactions between ultramafic/mafic rocks and water**
eg Serpentinisation

$$3Fe_2SiO_4 + 2H_2O = 2Fe_3O_4 + 3SiO_2(aq) + \mathbf{2H_2}$$

**Image:** Serpentine rock.
© iStock.com / FokinOl.

**2) Radiation splitting water molecules**
eg Radiolysis

$H_2O$ — IONISING RADIATION FROM U, Th, K → $e^-$, $HO^-$, $H^+$, $HO_2^{3-}$, $H_3O^+$, $H_2O_2$, $\mathbf{H_2}$

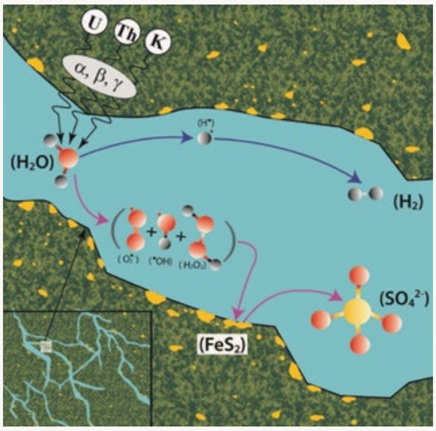



**Image:** Typical radiation water splitting reaction in water filled cracks in rock.

Additional processes currently under investigation include additional redox chemical reactions with iron-rich rocks including banded iron formations[41, 70] and mechanical crushing along fault boundaries[67].

Source: Figure after Sherwood Lollar *et al*, 2014[32].

### 1.3 Hydrogen generation by radiolysis and water-rock reactions

There are many water-rock reactions that can produce hydrogen as a by-product. Many are hydration reactions affecting ultramafic and mafic rock – sometimes broadly all referred to under the umbrella term 'serpentinisation'[71, 56, 72]. Models and laboratory experimentation converge on peak hydrogen yield efficiency at temperatures of 300°C, falling off sharply at higher temperatures[59, 73, 74, 75]. Recently there has been significant research into a range of conditions under which there is significant hydrogen production at lower temperatures (<100°C)[56, 72]. This finding opens up much more of the Earth's crust as potential areas of hydrogen production. The porosity/permeability distribution and migration of groundwaters through geologic systems will also determine water availability, reaction timing, and the ability to achieve theoretical hydrogen generation volumes. This will likely link closely to fault distribution, terrain compression or extension and regional tectonics.

Classic 'serpentinisation' involves hydration of rocks containing iron Fe (II) and magnesium Mg – bearing minerals, resulting in the reduction of water to hydrogen and oxidation of Fe (II) to form Fe (III) – minerals. Olivine and pyroxene found in ultramafic settings are the main sources of Fe(II) and have received considerable attention as those involved in hydrogen generation, reacting to form serpentine minerals. The iron content alone does not control hydrogen yield. The formation and distribution of secondary minerals, controlled by the local chemistry, determines the reaction product Fe (II) or Fe (III) and plays a significant role in hydrogen generation efficiency.

Mafic rocks such as basalt also contain significant Fe (II). Modelled hydrogen yields from mafic rocks are 10 – 100 times lower typically than those of peridotite (ie ultramafic) but, because they are more abundant, they may also form a significant crustal hydrogen source. There is considerable ongoing research to determine the hydrogen producing potential by oxidation of other iron-rich rocks such as banded iron formations (BIFs) and metasedimentary rocks with high iron content[76, 70].

In contrast to water-rock reactions, the generation of hydrogen by radiolysis is a simpler mechanism to quantify. It occurs in all crystalline rock types and is potentially a more universal mechanism than serpentinisation[12, 32, 77]. The dependence of hydrogen yield is dominated by:

- uranium, thorium and potassium concentrations in the surrounding rocks;
- water availability in the rock fractures;
- pore space; and
- time.

Yields are most significant in terrain that has been enriched in uranium and thorium or have been closed systems (either in terms of tectonics or hydrogeology) for long time periods such that the products of the reactions can accumulate over time[78]. Like water-rock reactions, hydrogen production is dependent on water availability within the source rock. Unlike water-rock reactions, because the yield is a slow and continuous process, it is dependent on the time-integrated water content of the source rock over its geological history[53, 32, 79].

## 1.4 Hydrogen migration

Some hydrogen source rocks, such as those in Precambrian crust[32], or uranium and thorium enriched sediments[80], have preserved the gases generated within them for hundreds of millions to billions of years because of their low permeability[12, 80, 81]. In contrast, in other settings rocks generating hydrogen by water-rock reactions, such as ophiolites, may have that hydrogen released by increased fracturing due to natural processes (impacts, uplift, tectonic activity) or anthropogenic activity (mining or drilling)[78]. In exposed ophiolites, greater penetration by surface waters may drive faster water-rock reactions. However, the related propagation of fractures may provide pathways to vent hydrogen to the atmosphere as fast as it is generated (over anthropogenic timescales). Water ingress/supply into the crust and the important controls exerted by permeability and porosity evolution of the crystalline basement[82, 83, 78] are critical considerations when evaluating regional hydrogen prospectivity.

The trapping of hydrogen requires a geological structure, closed either by the geometry of a reservoir or a reservoir stratigraphic pinch out against impervious rocks (eg those that limit transport and provide a mechanism for gas accumulation). In all systems, reservoir rocks where hydrogen is trapped may be of a different age or mineralogy than the source rocks within which production occurs. Once trapped, the preservation of the accumulated hydrogen will be a function of the extent of contact with oxygenating gases or fluids, or microbiological sinks (see Section 2.2).

The most desirable exploration targets will neither be too deep and isolated (very low permeability), nor too open and prone to loss of hydrogen as it is generated. Sedimentary basins overlying hydrogen producing crystalline basement rocks are a notable example of an environment that may accumulate hydrogen gas. Helium accumulations have been identified for decades in the contacts between major sedimentary basins and the underlying crystalline source rocks[50, 84, 85, 86]. Hydrogen may similarly be released from low permeability source rocks into nearby higher permeability features such as faults, or fractured rock and porous sedimentary strata in contact with these features. Transportation of hydrogen out of the source rock may be driven by pressure gradients generated by rock density decrease during hydration, increase in fluid pressure due to burial, temperature changes or gas generation, or a change in the regional tectonic stress regime. In these cases, hydrogen transportation will be advective, carried in another fluid.

In other systems, gas diffusion rather than advective transport may be important over different spatial and temporal scales. Helium will diffuse out of uranium- and thorium-containing minerals into the same fracture fluid or pore-space where water-rock reactions generate hydrogen, or where water is subject to radiolysis. This means that hydrogen to helium ratios for production from radiogenic elements such as uranium and thorium can be predicted[12, 32, 79].

Furthermore, comparing diffusion profiles for the noble gases (neon (Ne), as well as helium) can be used to quantify the diffusive loss to a system, which can then be used to estimate potential hydrogen transport due to diffusion[53]. In this way, the ability of a sedimentary system in contact with the basement rock to build up potential accumulations of basement-derived helium and hydrogen can be estimated[12]. In this case, gas phase formation is dependent on both the quality of the seal overlying the contact strata and the architecture of the sedimentary column controlling the diffusive gradient of gases to the near surface[85]. Overall, noble gases coupled with hydrogen exploration can provide a powerful tool to not only constrain sources but to identify transport processes for hydrogen.

### 1.5 Resource: field size distribution, fluxes, and co-produced gas

It took more than 100 years for the petroleum industry to work out the basics of petroleum systems analysis. The emergence of an understanding of how petroleum source rocks form and expel their products, and mechanisms of petroleum migration and entrapment processes, were not forthcoming until the 1980s. Today, the oil industry has a well-developed understanding of oil and gas field reserve size and distribution[87, 88] although even now understanding is semi-quantitative, leading to a chance of success in petroleum exploration of about 30%[89].

There is as yet no publicly available data for hydrogen resource or reserve field size to populate statistical distributions and it is premature to quantify these parameters. Flux (leakage) size has been used to understand the potential for societal benefit. Zgonnik[22] provides an empirical referenced source of different sourced hydrogen fluxes. An update to this table for hydrogen flux from global subaerial volcanoes is provided by Aiuppa and Moussallam[90]. Box 2 provides a summary of the flux estimates relevant to continental settings. For reference $1.0\times10^{11}$ moles of hydrogen (0.2 million tonnes hydrogen), generates the energy equivalent to ~$7\times10^5$ tonnes of oil, or 0.017% of the crude oil produced globally in 2022[55]. Accumulation of a portion of this on geological timescales would be significant.

A recent paper[33] provides a modelled range of <1 to 1,000 million tonnes $H_2$/yr, with a most probable estimate similar to that of Zgonnik[22] eg 24 Million tonnes $H_2$/yr. This mass balance model includes as potential resources volcanic and hydrothermal sources as well as $H_2$ from serpentinisation, radiolysis, oxidation of iron-rich rocks, and potentially from organic-rich rocks, while noting that only a small fraction (2%) might be recoverable[33]. More controversially, they suggest that while the exact numbers are highly uncertain, hydrogen in fluids upwelling from the mantle and somehow from metal hydrides and other rock-bound hydrogen in the core could increase estimates to 25,000 million tonnes $H_2$/yr.

Much public confusion has sometimes arisen in discussion of water resources from reports of ‘oceans’ of water supposedly discovered in the deep Earth or even on the Moon. Confusion arises because the numbers on which these reports of ‘oceans of water’ are based are not for $H_2O$, but in fact based on H-bound to rocks and minerals (eg ringwoodite[91]) and as such not available to circulate in the water cycle[78]. Similar caution is urged here, where Ellis and Gelman[33] suggest that including ‘deep hydrogen sources’ from the mantle or core might support maximum hydrogen generation rates of 25,000 million tonnes $H_2$/yr. While the high pressure and low oxygen fugacity in the deep mantle suggest molecular hydrogen and $CH_4$ do form the main mobile H-species at great depth, decreasing pressure and increasing oxygen fugacity in the upper mantle and crust results in the major volcanic gases reaching the surface as $H_2O$ and $CO_2$. Evidence for this is readily found in studies of ocean island/mantle plume volcanism[55]. Further continental mantle-$^3$He flux is well constrained, and based on the mantle $^3$He/H molar ratio of $1.14 \times 10^{-10}$ restricts any mantle H contribution to volcanic water vapor to 2.4 million tonnes /yr[55], a well-established value well below the one Ellis and Gelman suggest.

Overall, care must be exercised in using the flux data to extrapolate resource estimations as not all source environments provide focusing or trapping structures (eg mid ocean ridges) while others may be associated with very high levels of co-gas that makes for non-viable economic recovery. Currently the uncertainty on the volume of hydrogen is huge and exploration remains a high-risk proposition.

BOX 2

## Global natural hydrogen flux

Global hydrogen flux (hydrogen leakage to the surface) estimates provide a starting point in considering the overall potential of natural hydrogen as a resource. Table 25 in Zgonnik (2020)[22] provides an empirical compilation of global hydrogen flux estimates for different geological systems. An estimate of the total geological hydrogen flux is derived by considering the highest estimate, when there is a range, and estimating the average for each system considered and summing these. This provides an optimistic total global flux of 23 million tonnes $H_2$/yr. Several of the systems such as 'Mid-Ocean rift systems', 'Ocean Crust Oxidation', 'Ocean Crust Serpentinisation', 'Basaltic Layers of the Oceanic Crust' and 'Mid Ocean Ridge Volcanoes' are in fact subsets of the same oceanic crust processes, and lead to some level of double counting in the published total geological hydrogen flux. Importantly, hydrogen generation in the oceanic crust is unlikely to provide an environment in which accumulation of a commercial gas phase reservoir is viable however, so the table (below) focuses on possible flux from continental systems where commercial exploitation would be easier at least initially.

The focus is on three settings (see table below). 'Volcanoes and Hydrothermal Systems' and 'Subaerial Volcanoes' are each considered to be separate systems in the Zgonnik (2020)[22] compilation, resulting in another double counting in deriving the geological summation. The value from Holland 2002[92] that was often used to represent 'Volcanoes and Hydrothermal systems' is an order of magnitude higher than many more recent estimates. Sleep and Bird (2007)[93] suggest that the Holland (2002) level is not supported by the iron content of the host magma, and their own estimates (under 'Subaerial volcanoes') converge with those of Canfield *et al* (2006)[94] and Hayes and Waldbauer (2006)[95]. A more recent assessment of global volcanic gas flux (Aiuppa and Moussallam, 2023)[90] is in agreement with the previous lower values for continental settings. This latter value is therefore used in the flux assessment from volcanic flux in continental settings (eg magmatic origin) in the table below. For comparison, the table shows flux estimates from Ophiolite massifs[96], and the Precambrian continental crust[23] in both cases largely attributed to water-rock hydration reactions (serpentinisation) and radiolytic processes. Including the volcanic gas flux, a total continental geological hydrogen flux of <1.74 million tonnes $H_2$/year can be calculated. Excluding the volcanic gas flux (as noted unlikely to be a commercial target), the continental geological hydrogen flux can be estimated to be <0.74 million tonnes $H_2$/year. This is substantive, all the more so if such hydrogen fluxes can accumulate in subsurface traps, year after year, over long geological time-scales.

Discoveries of such significant accumulations of natural hydrogen in the continents, in traps that are sustained by hydrogen fluxes of this magnitude, could be a game changer for the energy transition globally, even if only a small proportion of these are accessible.

### Global hydrogen flux estimates

| Hydrogen Source | Million tonnes per year | Reference |
|---|---|---|
| Continental Volcanic | 0.06 – 1.0 | Aiuppa and Moussallam 2023[90] |
| Precambrian Continental Crust | 0.04 – 0.38 | Sherwood Lollar *et al*. 2014[23] |
| Ophiolite Massifs | 0.18 – 0.36 | Zgonnik 2019[98] |
| **Total Continental Flux** | **<1.74** | **All continental sources** |
| | **<0.74** | **Continental crust and ophiolite only** |

# How does hydrogen migrate to shallow groundwater, soils and atmosphere?

Hydrogen and other crustal fluids (eg helium, natural gas, carbon dioxide, brines) can migrate from their source rocks or from breached traps in the deep subsurface to shallow, near-surface environments and the atmosphere by advection (in fluids) through geologic permeable media (eg bedrock, soils) or preferential naturally-occurring flow paths like open faults and fractures, or pathways artificially created by abandoned boreholes or leaky wellbores (Figure 5).

Hydrogen can migrate as a gas (eg free gas) or in an aqueous solution (eg dissolved in saline brines or brackish to fresh groundwater) and be transported vertically by diffusion and/or horizontally by advection in more permeable units[85]. The presence of relatively low-permeability strata, such as shale and salt, can inhibit advective transport of hydrogen and serve as cap rocks for hydrogen accumulations. Over time, hydrogen and other small molecules, such as helium, can be transported across low permeability strata by diffusion, this can be quantified by measuring both hydrogen and associated noble gases[85].

Decades of research on subsurface storage and transport of natural gas, $CO_2$, radionuclides and wastewaters can provide insights into hydrogen transport. However, the flow properties of hydrogen are different from these other fluids and constituents, and there are a lot of uncertainties. Hydrogen and helium are less dense and more buoyant than carbon dioxide, methane and nitrogen, and thus are more likely to be transported and dispersed in the subsurface[26, 85]. However, there remain significant gaps in applying these basic principles to make predictions of hydrogen accumulation, storage and potential environmental impacts[97, 98]. Wider application of noble gas geochemistry can help identify these physical processes as described above.

FIGURE 5

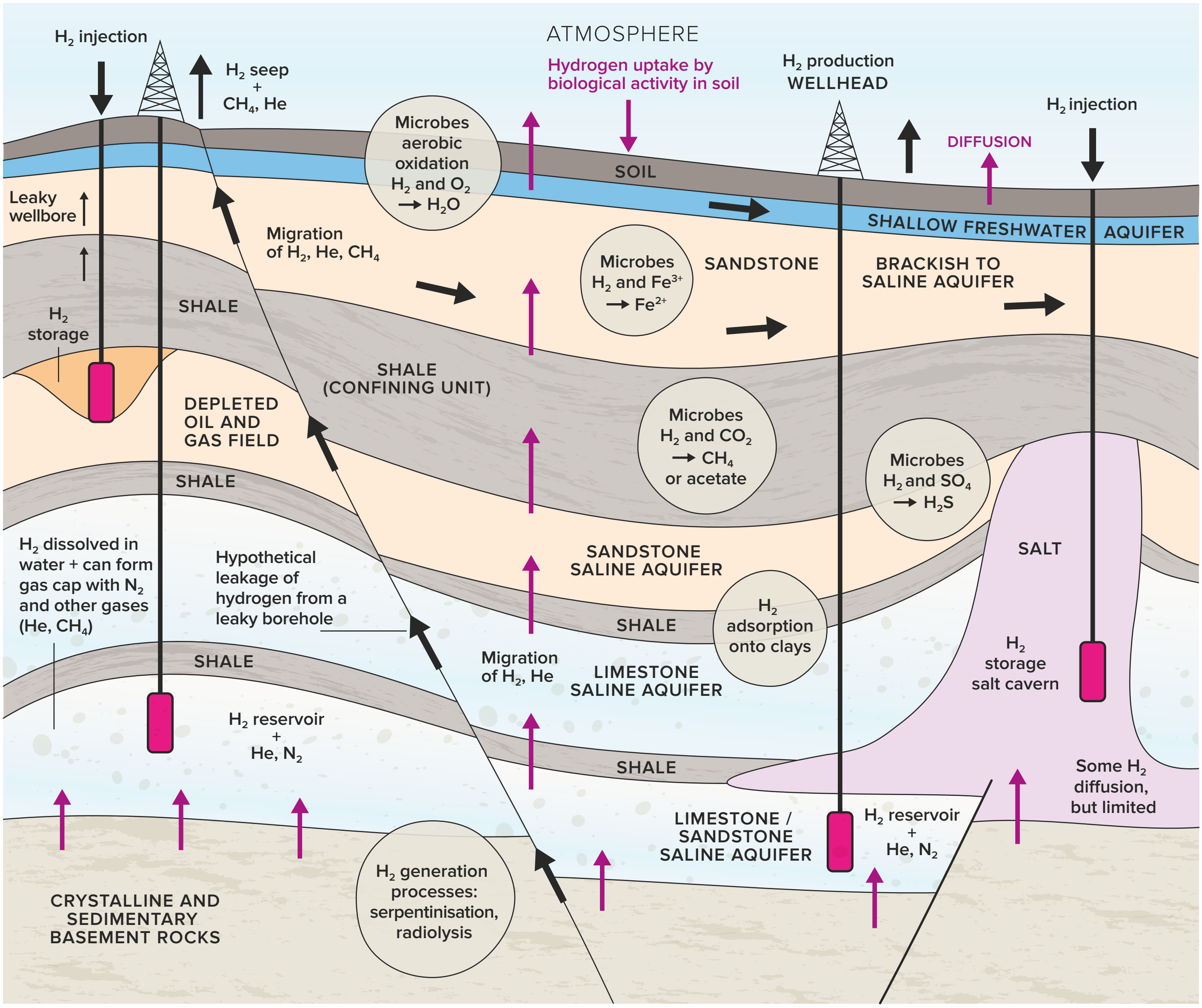
Schematic cross-section of hydrogen transport from accumulations in the deep subsurface to near-surface environments, including shallow aquifers, soils, and the atmosphere.

Upward arrows show natural release of hydrogen (and co-emitted gases) from seeps, springs, and soil. Downward arrows above the ground show hydrogen uptake by biological activity in soils.

KEY

Advection

Diffusion



## 2.1 Natural hydrogen seeps as analogues

Natural hydrogen seeps or springs are locations where hydrogen is released from soils at relatively high concentrations by advection, typically along faults, while sub-circular depressions occur with more diffuse hydrogen leakage at lower concentrations. Hydrogen seeps, springs, and sub-circular depressions have often been attributed to deep geologic sources of hydrogen and used as a prospecting tool (see Box 3).

However, it is important to note that, hydrogen released from these features may be entirely biological in origin, for example, from microbial activity in water-saturated soils[42]. Further, not every subsurface hydrogen reservoir is associated with surface hydrogen seeps. Therefore, surface expressions or measurements of hydrogen may not be a reliable indicator of the presence of deeper geologic reservoirs of hydrogen.

BOX 3

### Potential for false positives (artifacts)

Studies often focus on measurements of hydrogen in soil or fluids recovered from drilling activities. Detail of the protocol required to ensure robust observations in, for example, soil gases exist[41, 42, 99]. Uncertainty caused by poor measurement protocol, reliability of equipment and calibration against temperature dependence or false signals from co-gas presents a risk in quality control of historical data.

Interpretation of measurement is also critical, even when robust. Artifacts caused by hydrogen generated by drilling (sometimes called ‘drill bit metamorphism’) or pipe corrosion are well-established. Recent work reviews the risk and highlights the importance of removing these false signals from consideration of local or regional hydrogen flux estimates[43]. Hydrogen generated by microbial activity can also generate false signals, with high concentrations of biological hydrogen, methane and carbon dioxide resembling geological seepage.

Soil gas hydrogen concentrations as high as 1% have been identified as biologic in origin[42, 100]. Co-occurrence of helium in samples would help resolve some natural hydrogen sources from near surface artifacts.

The way in which soil gas measurements are converted into a flux is determined by whether they have diffused from depth into the soil or flowed into the soil along faults and cracks (called advective flow). A diffusive mechanism is often assumed and likely to require a larger local flux to sustain soil gas concentrations than advection. Geological seepage of hydrogen at Chimera, Turkey, reaches the surface through advection[101]. A systemic quality control review of the literature is not available. This will need to consider measurement robustness, artifact generation as well as propagation of origin and mechanism uncertainty to identify the good from the bad.

Hydrogen is often co-emitted in hydrogen-rich seeps with hydrocarbons (primarily methane, $CH_4$) and other gases (He, $CO_2$, $N_2$) (see Figure 1). These gases may have a similar origin as hydrogen (eg helium from crustal sources) or come from other sources. Measuring the isotopic signature of these gases can distinguish the sources and provide insights into the origin of co-migrated hydrogen. For example, if there is no indicator of co-associated methane, carbon dioxide, nitrogen and noble gases, and especially if the associated nitrogen, oxygen and or noble gases are atmospheric in origin, it is unlikely that hydrogen reflects a deeper accumulation of natural hydrogen of economic potential; rather, hydrogen may be more likely sourced from near-surface microbiological activity.

The concentration of soil gases, including hydrogen, can fluctuate on sub-daily timescales from atmospheric conditions, biological activity, lunar tide etc, as well as from sampling activities (eg drilling monitoring wells, installing soil gas samplers)[102]. These background fluctuations are important to measure to distinguish shallow microbiologic hydrogen from deeper sources, noting that soil hydrogen data is limited[102, 43]. Surface seepage rates for natural hydrogen have been reported to range over three orders of magnitude, from approximately 9,000 to 5,000,000 grams per $m^2$ per day[103]. Continuous flames have been reported for thousands of years and burned vegetation, including trees, have been observed around hydrogen seeps[101]. While hydrogen is flammable when mixed with air or methane, it tends to diffuse into the atmosphere and does not accumulate in depressions and cause human health hazards like denser carbon dioxide.

Hydrogen is an indirect greenhouse gas. When hydrogen is released to the atmosphere a majority (70 – 80%) of it is consumed by diffusion into soils and biological activity[103, 104]. The remaining hydrogen reacts with hydroxyl (OH) radicals in the atmosphere to produce other greenhouse gases, such as methane, ozone, and water vapor[105, 106]. Thus, hydrogen is considered to have an indirect effect on global warming.

Where subsurface hydrogen migrates into shallow aquifers, it could enhance microbial activity that increases greenhouse gas emissions through production of methane or decrease water quality by production of reduced iron and hydrogen sulphide. Reduced gases, such as hydrogen sulphide and methane, can be corrosive for infrastructure in near surface (eg underground pipes) and deeper (eg wellbores) environments. Not all these impacts can be characterised as negative. For instance, stimulation of natural microbial communities by input of hydrogen may enhance metabolisms that improve water quality, such as bacterial reduction of nitrate. How hydrogen seepage affects ecosystems and infrastructure needs further investigation[107].

## 2.2 Hydrogen sinks

### 2.2.1 Microbial sinks of hydrogen

Hydrogen is highly reactive and likely to be consumed, or transformed into other molecules, including gases, by biotic or abiotic processes as it migrates from subsurface sources to shallow aquifers, soils, or the atmosphere[36, 78, 108].

Hydrogen is an energy source for numerous microbial communities that are commonly found in deep subsurface to near-surface environments and has a greater potential for biodegradation compared with other gases[109, 110]. These hydrogen consuming microbial processes have been widely documented in deep saline aquifers, oil and gas reservoirs, fresh to brackish aquifers (eg associated with buried organic matter), saturated soils, wetlands, and other subsurface environments devoid of oxygen.

Under oxygenated conditions, near the surface (eg surface waters, aerated soils), hydrogen can be further consumed biologically by aerobic hydrogen oxidation[111]. Soils, wetlands, forest, and grassland ecosystems are similarly sinks for hydrogen that is released to the surface naturally or anthropogenically. While rates of hydrogen consumption by various microbial processes have been determined in the laboratory, there is little information about the rates of these processes in nature at larger scales[47].

Microbial communities that consume and produce hydrogen can be found from the Earth's surface down to several kilometres deep in crustal environments[112, 78]. Hydrogen generated by abiotic processes, for example in crustal environments, may migrate into a zone of more robust microbial activity. In this case, hydrogen is likely to be consumed to some extent by microbial processes. In other deep environments where microbial communities persist, the preservation of hydrogen concentrations may be due to several factors including rate-limitations such as available nutrients or carbon-sources necessary for microbial activity[113, 114]. Rates of hydrogen consumption are a function of the specific setting and nature of the microbial populations present. At temperatures within the range for life (nominally less than 122°C), one of the key controls on the level of biomass and biological activity is, on an overarching level, related to the penetration of groundwaters that both control the availability of key nutrients for life and allow life to migrate and propagate. The greater the extent and depth of penetration of surface-related water cycle, the greater the biological activity and the greater the tendency for hydrogen levels to have been locally reduced[35, 36, 78]. Ideal traps for hydrogen may be those that are hydrogeologically tight enough to limit microbial activity but open enough to provide the water-rock ratios sufficient to sustain hydrogen production[26, 115, 116].

Despite some knowledge of subsurface microbial communities that cycle hydrogen, the understanding of the distribution of microbial communities and their function across crustal environments is only in its infancy. New, novel metabolisms are being discovered[112, 117]. Characterisation of subsurface microbial communities from dedicated scientific boreholes and opportunistic sampling from, for example, existing and exploratory boreholes or underground laboratories and mines will help advance understanding of subsurface hydrogen cycling. These insights will also be valuable to other industries exploiting subsurface resources that may be impacted by biological activity (eg hydraulic fracturing for oil and gas production and storage of nuclear waste and anthropogenic carbon dioxide, for instance).

### 2.2.2 Abiotic sinks of hydrogen

There are many abiotic sinks in the deep subsurface that do not involve microorganisms. These include chemical reactions, such as abiotic methane formation, dissolution of rocks and minerals, and adsorption onto clays, as well as the physical sinks related to diffusive or advective transport already covered above. Just as microbial activity can consume hydrogen, non-biological (abiotic) chemical reactions in the subsurface can also consume hydrogen and in some cases produce methane and other small hydrocarbon compounds[118, 119, 114]. That said, methane and other hydrocarbons are volumetrically much more likely to be produced by conventional thermogenic and microbial processes[120].

Increases in hydrogen concentration of formation waters makes fluids more acidic, which can change chemical equilibrium and lead to precipitation or dissolution of minerals. Hydrogen can also adsorb onto clay and organic matter surfaces[8]. These gas-water-rock reactions may be a sink for hydrogen and potentially alter rock porosity and fluid migration pathways. The rates of these reactions are relatively unknown, yet necessary to parameterise geochemical models to make predictions on the fate and transport of hydrogen in the subsurface. Ellis and Gelman[33] for the purposes of their mass balance model assigned a $H_2$ consumption loss of between 0.1 and 10%, but field studies for locations of high microbial activity have shown local loss may be much higher[35, 36].

Overall, hydrogen is both consumed and produced by chemical reactions with fluids and minerals, and microbial activity in the subsurface[12]. A pertinent question might be, how would hydrogen exploration (and eventual exploitation) change the nature of this balance for both abiotic and biological sinks? To date, few studies have addressed the impact of anthropogenic activities on subsurface microbial communities and elemental cycling[121]. Case studies from hydraulic fracturing[122], nuclear waste disposal[123], and geologic carbon sequestration[124] may provide insights into the effects of these activities, and possibly hydrogen exploitation and storage, on subsurface chemistry and microbiology. In addition, there is an opportunity to address this question more comprehensively by investigating the linked impacts and effects of both conventional energy as well as green energy proposals and other uses of the subsurface.

# Creating a commercially viable product

A competitive product and an efficient market are needed for commercial success. The right environment is necessary to attract investment, build out the required infrastructure and manage production. For natural hydrogen, multiple models for commercialisation exist depending upon the location and scale of production and the market; from large-scale global networks to smaller-scale local-regional developments[125]. As development of natural hydrogen projects progresses, so does data certainty. Assessments on cost, environmental impact (ie life cycle assessment; LCA) and social impact will also increase in quality with advancing data certainty and availability. At that point, the true effects of industrial-scale global production can be determined. Extraction, economic and impact modelling for natural hydrogen should be continuously enhanced as both experience and scale are developed, to maintain science-based deductions on the opportunities and risks for the sector in real-time.

### 3.1 Commercial production of natural hydrogen

As noted in Section 1 of this report, reliable estimates of natural hydrogen production potential are not currently known or well documented in public[125.] Some exploration and detection studies have been conducted across the globe. Additionally, national and state/provincial agencies are producing maps for hydrogen exploration based on reported hydrogen to date and geologic/mineralogic terrains likely to sustain hydrogen production. Despite this, to date, there is only one locality (Bourakébougou, Mali) where its detection is known to have led to economic use, although Helios Aragon's Monzón Field in northern Spain has progressed to planned production (see Section 3.2).

For a resource like natural hydrogen to have commercial potential, proposed development projects of hydrogen reserves need sufficient marketable quantities to attract potential investors[126]. These are measured against three key parameters to ensure the commercial viability of any production project:

- Production rates to deliver hydrogen at a consistent rate that justifies the investment in production infrastructure.
- Hydrogen purity, which influences the market the reserve can supply, its market value and its carbon intensity.
- Proven reserves, with a high degree of certainty of being commercially recoverable under current economic and operational conditions, including local, regional or global market demand (see Section 3.3 and 3.4).

Recently, naturally occurring hydrogen has sparked intense exploration activities in several countries across the world, including France, USA, Australia, Spain and Brazil. Private companies and academic research laboratories are committed to exploring this potential primary energy source, with the aim of identifying sites that meet the three key criteria for commercially viable natural hydrogen reserves. To date, a few hydrogen flows have been documented in surface springs and dry seeps located in ophiolitic massifs with values ranging from a few kilograms to a few tons per year[61]. A recent finding in the deep chromite Bulqizë mine in Albania[25] reported focused advective outgassing of nearly pure hydrogen (84 vol%) at a rate of 11 tons per year and up to 200 tons per year when considering the total output of the mine[25]. For context, a typical ammonia/fertiliser plant requires more than 100,000 tons of hydrogen per year.

Rather than focusing on single locations to derive estimates of potential hydrogen flux, most investigations today have undertaken an analysis based on global distribution and knowledge of geologic terrains producing hydrogen. If a small fraction of these global estimates could be accessed, natural hydrogen may make a tangible difference to the low carbon energy transition. The key challenge in moving natural hydrogen to the next stage will depend on if and where major finds are discovered in the current global exploration race. If proven reserves are present, other parts of the hydrogen value chain will need careful consideration, including the existence of suitable infrastructure and access (eg transportation and storage), hydrogen price and market conditions, extraction technology, the proximity to consumers, regulatory and environmental factors, and the social license to operate.

### 3.2 Methods of extracting natural hydrogen

Extracting natural hydrogen from underground reservoirs is still an emerging field, but initial techniques are likely to involve adapting established oil and gas industry techniques while taking account of hydrogen's unique properties[125]. Indeed, locations that have issued hydrogen permits to date have taken this approach. For example, Canadian provinces that have acted on this issue to date have addressed hydrogen permits and leases under the processes for helium, which falls under the Oil and Gas Registry Regulations (OGTRR)[127]. Standards in the oil and gas industry have long guided best practices in material selection, reservoir evaluation, and integrity assessment.

While these standards provide a strong foundation, hydrogen's small molecular size, high diffusivity, and reactivity may introduce specific challenges that necessitate additional measures such a high alloy steel, or anti-microbial treatment to reduce biofouling and corrosion that might be exacerbated by hydrogen availability. Research into the specific impacts of hydrogen on materials like metals, elastomers, and cement is ongoing, with the aim of refining or establishing new standards suited for long-term hydrogen exposure.

Monitoring, mitigation, and remediation for natural hydrogen production require a tailored approach that builds on oil and gas practices. By integrating advanced monitoring systems, hydrogen-specific materials, and targeted remediation techniques, the hydrogen industry should be able to develop safe, efficient and environmentally responsible production. Additional expertise will be needed in hydrogen-specific areas, such as gas handling safety, hydrogen purification processes, and material selection[128]. Other environmental elements common to conventional oil and gas will apply here too, including impact of energy extraction on subsurface microbiology and groundwater quality.

#### 3.2.1 Hydraulic fracturing

Depending on the geology of the reservoir, extraction methods may include directional drilling to access pockets of trapped hydrogen. Note that the USA ARPA-e program, which focuses on generating 'geologic hydrogen' (see definitions in Introduction), involves the injection of fracturing fluids to enhance hydrogen generation and flow. Natural hydrogen as defined in this report does not involve such fracking.

### 3.3 Supporting resource requirements

Before reaching the market, extraction and handling of hydrogen will use a variety of resources, such as building materials, fuel, electricity, water, and chemicals. Compared with other types of hydrogen (and even other fuel products), natural systems will likely require slightly fewer resources to extract due to the purity of the expected gas and the flow available from wells. Unlike oil and gas, hydrogen often requires high purity levels to meet commercial standards, especially for applications in fuel cells and energy storage. Techniques like pressure swing adsorption (PSA) or membrane filtration are commonly used for hydrogen purification and will be integral in ensuring the gas meets market requirements.

The areas of high resource impact can be identified by breaking the supply chain into three major sections:

1. **Exploration and drilling**
   Drilling rigs and associated equipment often require substantial energy inputs, and in the UK, this energy may be drawn from a mixed electricity grid that includes both renewable and fossil fuel sources, in addition to materials used to create infrastructure for extraction.

2. **Water Use, maintenance and management**
   In some natural hydrogen extraction processes, water may be used for cooling or other auxiliary processes. This can be an issue in some parts of the world where water is scarcer. For more advanced project development stages, localised water scarcity indices can be combined with life cycle analysis to give specialised ecological impacts of high water consumption.

3. **Energy consumption for extraction**
   Once natural hydrogen is located, electricity is required to power continuous production and fuel/electricity is needed to transport the hydrogen to market. The scale could be based on similar gas extraction systems, but ultimately would rely on many factors including gas flow, equipment efficiency, power quality and more.

### 3.4 Cost to extract

Currently, 74 million tonnes of hydrogen is produced annually around the world[5], primarily from methane steam reforming at a cost of approximately $0.8/kg. The hydrogen market is projected to grow to 220MTper year by 2050, with much of the production coming from blue hydrogen, at $1.2 – 1.5/kg expected costs[129]. According to Thunder Said Energy[129], green hydrogen is currently expected to cost around $7/kg.

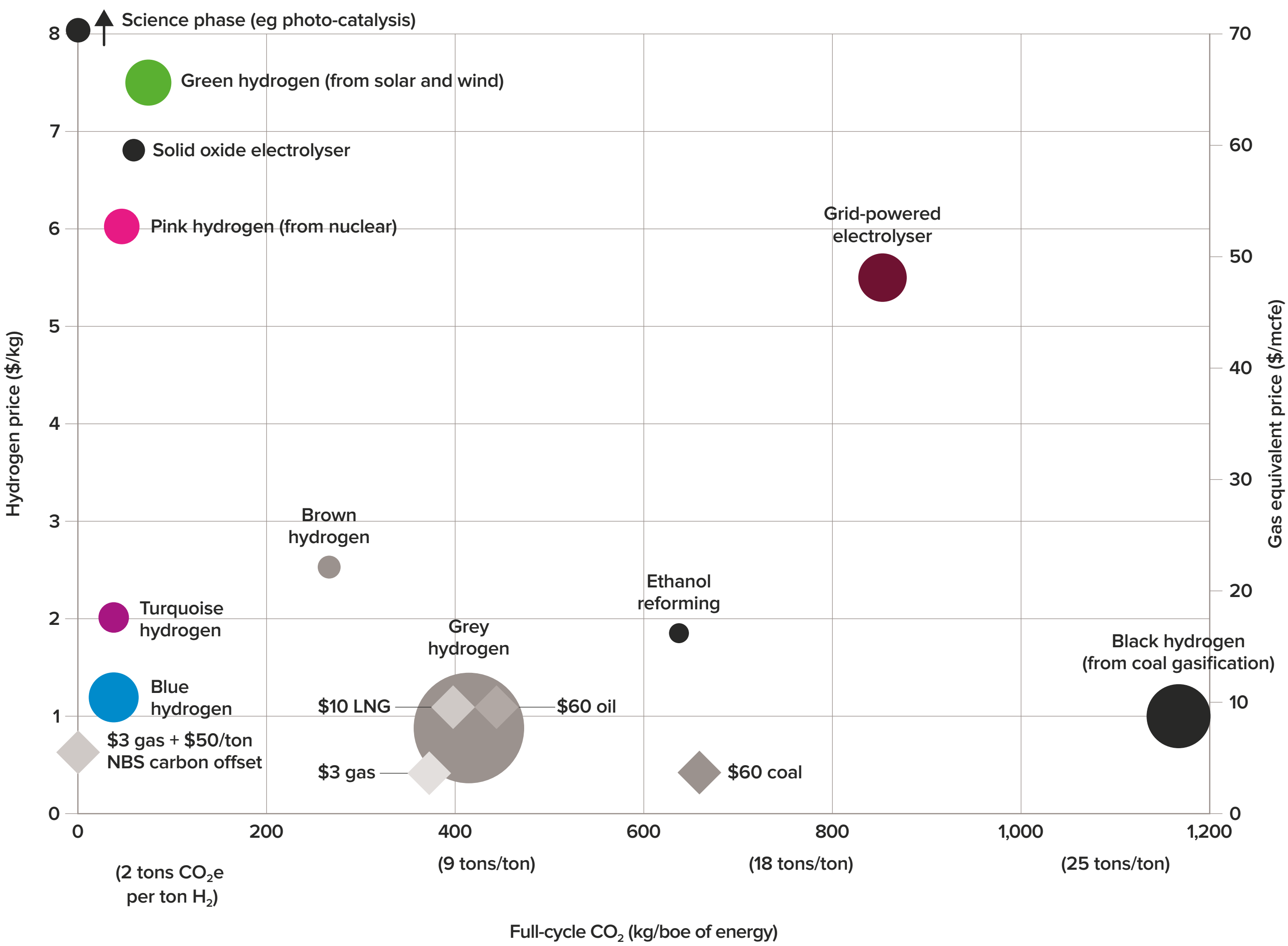
Figure 6 shows estimated costs for all colours of hydrogen against their estimated carbon footprint, with blue hydrogen being the most economical (with estimated costs of $1 – 1.5/kg, assuming ~90% of natural gas carbon dioxide is captured and stored).

Hydroma, citing the Bourakébougou Field in Mali, have argued in news reports that natural hydrogen production costs can be as low as 0.5 $/kg[130]. A key target that many natural hydrogen explorers aim for is an estimated cost of around 1$/kg[102, 131, 21]. Recent arguments have been presented that natural hydrogen could be recovered from the Earth's subsurface, with costs ranging from $0.3 – 10/kg[129].

In fact, the true cost of natural hydrogen remains to be proven since it has yet to be produced and sold in quantity. Analysis[129] of natural hydrogen highlights the importance of purity to the cost of hydrogen. Natural hydrogen at higher purities and volumes should be able to compete with grey hydrogen for cost and with green hydrogen for emissions.

FIGURE 6

Estimated costs and carbon footprints for various hydrogen production methods




Source: Thunder Said Energy[129].

The cost of natural hydrogen will therefore depend on several parameters such as the productivity of the field, the number of wells in the field, the depth of the wells, the existing infrastructures and the proximity with the consumers. Currently, most hydrogen is produced next to the consumer to avoid the cost of transportation. Therefore, natural hydrogen produced next to concentrated regional industry hubs may be a jumping off point for the sector.

Estimating the cost of natural hydrogen from 'the well head' (and beyond to account for the entire value chain involved in transportation, purification, storage, and delivery) will necessarily be more complex. When comparing natural hydrogen cost with one of the other hydrogen production methods, it is important to make sure that it is the end-user cost that is compared to avoid misleading conclusions.

## 3.5 Environmental issues and waste disposal considerations

Life cycle assessment is an effective tool for analysing a range of different impacts, particularly greenhouse gas emissions, water and energy consumption and direct pollution of water bodies via on-site emissions. This is true even for very early-stage assessments. Recognising which inputs to the system are causing the largest environmental impacts can be valuable for sustainable project development. It is important to consider impacts across the entire life cycle.

LCA enables the assessment of indirect impacts that occur throughout the lifecycle of a product or process system on a global scale, offering insights that may otherwise be overlooked. This treats hydrogen as a product, including extraction and preparation. Many articles and studies exist for the other types of hydrogen and for natural gas extraction, which have been used for a comparative basis, but the ability to use primary public data for this study is not available[125].

Despite this lack of publicly available LCA data, some high-level commentaries can be made about potential environmental impacts. This gives a starting point for further discussion that enables inputs and outputs to be mapped, environmental impacts to be assessed, and R&D needs to be assessed as the nascent natural hydrogen sector develops. The critical aspects are:

a. **Infrastructure**
   The materials and energy consumed during the creation of foundations, transportation pipes and equipment are considered in this stage of the life cycle impact. Note that the relative impact of such inputs would be highly variable depending on expected hydrogen output of the system over its lifetime and it is key to develop understanding of energy efficiency per unit output as the technology develops to grasp the true lifecycle impact of this stage. It is important to consider the impacts of exploration and drilling, the source of energy consumed, water usage, and any infrastructure development.

b. **The processing stage**
   As with the majority of raw material upgrading a purification process, the energy consumed to bring a product to a sellable state is normally a key target for impact reduction. For natural hydrogen, there is an inherent advantage in that this processing stage would be minimal compared to incumbent technology or other commodities[125]. This will be directly matched to the output and as such, efficiency is key here, and minimising waste via leakage, environmental losses and unused energy inputs will help reduce the embodied impact of the system. It is important to consider processing and purification and any emissions from the process (eg venting or flaring).

c. **Land and water Impacts**
   LANCA (Land Use Indicator Value Calculation Tool) and AWARE (Available WAter REmaining) are methodologies used to assess the impacts of land use and water use within the context of LCA. Drilling and infrastructure development for hydrogen extraction may disturb soil layers, affect filtration properties, and alter water balance. In regions with limited water availability, the extraction process could exacerbate local water scarcity.

While natural hydrogen is expected to have a lower carbon footprint compared to hydrocarbons, the exploration and production of natural hydrogen pose both environmental and social challenges that must be carefully considered. As an extraction technology, it will inevitably have many of the same potential environmental impacts, need for regulation and monitoring and issues with social license that all extractive resources incur. The text below focuses on those that might be particular to hydrogen.

### 3.5.1 Above-ground environmental impacts

Increased hydrogen emissions into the atmosphere (above the natural flux) can have unintended climate consequences, due to hydrogen's role as an indirect greenhouse gas[39, 22]. However, it is important to note that hydrogen's Global Warming Potential (GWP) is significant and stronger than that of carbon dioxide, and that it remains much lower than that of methane over comparable time frames. This indicates that, although hydrogen can have indirect greenhouse effects, its impact on global warming is lower than methane, especially in terms of short-term climate effects. Studies show hydrogen's GWP100 (GWP over 100 years) ranges from 4.3 to about 12, meaning 1 kg of hydrogen can have a warming effect of 4.3 – 12 kg of $CO_2$ over a century. This range reflects advances in models that now account for hydrogen's combined effects in both the troposphere and stratosphere[132]. It has been suggested that if hydrogen is accidentally released or intentionally vented from production wells or pipelines, for example, it could have a significant impact on global warming[133]. Yet it is uncertain how much of the anthropogenic hydrogen would be taken up by soils, reducing its global warming potential. The technology to detect and measure leakage from infrastructure is not widely available. However, the development of innovative approaches for hydrogen gas detection and quantification[134].

As for all extractive resources that involve a gas phase, rigorous monitoring and containment, effective leak prevention measures, combined with accurate emissions monitoring, will be important components of the energy future.

### 3.5.2 Monitoring and reporting standards

Like all extractive resources the natural hydrogen industry will require the establishment of robust monitoring and reporting standards to accurately track environmental impacts, feasibility, and ensure compliance with regulations. Therefore implementing rigorous environmental monitoring frameworks from the start is crucial[135].

Early LCAs conducted on hydrogen technologies have shown that greenhouse gas emissions from production are highly sensitive to factors like gas composition, reservoir characteristics, and production methods[13]. For example, reservoirs with high hydrogen purity emit fewer greenhouse gases than those with mixed gas compositions, particularly if methane ($CH_4$) is present. Therefore, standardised monitoring and reporting protocols are essential to accurately measure emissions and ensure that the industry minimises its environmental footprint.

Finally, there is an urgent need to standardise how the Global Warming Potential of hydrogen is measured. While hydrogen itself does not directly warm the atmosphere, it can prolong the lifetime of methane, a potent greenhouse gas, by consuming hydroxyl radicals (OH) that would otherwise destroy methane. This secondary warming effect must be accounted for in hydrogen production and usage. Developing appropriate sensing technologies and monitoring frameworks will be key to mitigating these potential impacts and ensuring that hydrogen remains a viable low-carbon energy source.

# Establishing a market for natural hydrogen

Today hydrogen is not primarily used as a fuel. As discussed elsewhere in this report, most of the existing supply is grey hydrogen from steam methane reforming or methane pyrolysis, with a small (~0.1%) green percentage coming from renewable sources via electrolysis. About half of this is used for refining, with the remainder used to produce ammonia (for fertiliser production) and methanol (a precursor chemical)[136]. Nonetheless, hydrogen's potential to help achieve global net-zero targets has gained significant traction worldwide. As of 2023, 41 countries, have already established hydrogen strategies[7], recognising its potential to decarbonise hard-to-abate sectors such as heavy industry, transport, and provide large scale energy storage enabling a higher penetration of renewables into the energy mix, providing grid stability and energy security.

Natural hydrogen could support this expansion and diversify the global hydrogen supply. While natural hydrogen would require energy inputs to extract, purify, transport and store, the overall energy requirements for the entire lifecycle may be significantly reduced in comparison to green hydrogen[125]. For example, 500Mt of green hydrogen would require approximately 25,000 TWh of electricity[137]. In comparison to the high energy intensity of green hydrogen production, natural hydrogen could be considered a more energy efficient generation pathway as there is a reduced need for energy to be driven into production of the final product compared to other generation types of hydrogen. Hence, it could potentially be used at a greater scale than green hydrogen if it can be economically extracted. Although natural hydrogen research is in an early stage, preliminary results from one quantitative model for global natural hydrogen resource potential suggest natural and stimulated (geologic) hydrogen combined could meet 50% or more of the forecast demand for hydrogen by the year 2100[138, 33].

The scale and costs of extraction and use are to date, still highly uncertain, despite some groups suggesting low costs of less than $1/kg hydrogen[131].

A key consideration for natural hydrogen production is that it meets low carbon hydrogen standards as set within the international market. 100% purity natural hydrogen is highly unlikely in nature as most of the reactions that form hydrogen in the subsurface also produce carbon dioxide ($CO_2$), methane ($CH_4$), helium (He), nitrogen ($N_2$), hydrogen sulphide ($H_2S$) or argon (Ar) depending on the specific geological source rock (see Introduction). The UK Low Carbon Hydrogen Standard[139] was introduced by the UK government in 2023 to promote the production and use of low-carbon hydrogen. The standard requires that the hydrogen production method must emit less than 20g of $CO_2$ equivalent per megajoule ($gCO_2e/MJ$) of energy produced. This threshold includes emissions from the full lifecycle of hydrogen production and includes emissions during the production processes. To be considered low carbon, natural hydrogen will most likely require the removal and sequestration of these contaminant gasses[13], which will add technical and economic considerations to the extraction process.

### 4.1 Comparing production types of hydrogen

As with any new production technology, it is useful to compare with incumbent solutions. As outlined in the Introduction to this report, the multiple generation types or 'colours' of hydrogen (see Box 1) have their strengths and weaknesses. Green is but one of the many colours assigned to manufactured hydrogen in an attempt to show that the process by which the hydrogen is produced matters in terms of both carbon footprint and cost. For green hydrogen, electrolysis is a human instigated process that requires large quantities of water and large quantities of electricity (50 kWh and 9 to 29 kg of water for 1 kg of hydrogen produced). Table 2 outlines the manufacture method together with the quantity of hydrogen produced by each method (today), the range of carbon footprints which apply to such manufacture, the cost of each process in $/kg of hydrogen produced and a little commentary on the process and its sustainability. When discussing natural hydrogen, it is most typically directly compared against green hydrogen due to their comparably reduced environmental impacts. While environmental impacts are and should be of paramount importance in this discussion, it is important to consider several broad factors when comparing manufactured hydrogen types against each other to capture the broader estimated picture of their use.

These factors should include but are not limited to:

- Cost of production purification, transport and storage.
- Environmental impact including and beyond carbon and greenhouse gas emissions of the entire product lifecycle eg water use, land use, energy requirement, and sources as well as biodiversity impacts.
- Scalability and availability.
- Infrastructure requirements encompassing the resulting financial, social, and environmental cost of adapting existing infrastructure as well as development of new infrastructure.
- Feedstock availability and origin.
- Policy and Regulatory Support.
- Technological maturity and innovation potential.

TABLE 2

Natural and manufactured hydrogen.

| Colour | Energy source | Hydrogen source | Production process | $CO_2$ emissions ($kgCO_2$/kgH2) | Cost ($US/ $kgH_2$) | Notes |
|---|---|---|---|---|---|---|
| Natural | Geochemical reactions in the earth's crust | Connate water and minerals (mafic and ultramafic) | Gas expansion from subsurface ground waters and or on-going geochemical reactions | 0.4[13] | 0.3 – 10[129] | Reduced feedstock requirements compared to other generation types; quantities currently largely unknown |
| Green | Renewable electricity | Fresh water | Electrolysis | 0.3[140] | 4.5 – 12[141] | NA |
| Grey | Any electricity | Methane | Methane reformation | 9.8 – 13.7[137, 142] | 0.98 – 2.93[138] | Grey, brown and black hydrogen comprise ~99% of production in 2023 |
| Blue | National electricity grid mix | Methane | Methane reformation with CCS of resulting emissions | 0.8 – 8.8[13, 140, 143] | 1.8 – 4.7[138] | $CO_2$ captured & stored |
| Brown /Black | National electricity grid mix | Coal | Gasification | 20 – 25[140] | 0.45[144] | Grey, brown and black hydrogen comprise ~99% of production in 2023 |
| Orange[145] | Geothermal | Injected water | Direct generation from mafic rocks at depth | Unknown but low | Not known | Untried process |
| Pink | Nuclear generated electricity | Fresh water | Electrolysis | Unknown but low | Not known | NA |
| Turquoise | Renewable/ sustainable heat source | Methane | Methane pyrolysis | Solid carbon byproduct | Not known | |

Source: Developed from Gluyas *et al*. 2025[20].

## 4.2 Potential natural hydrogen markets

If commercial volumes of natural hydrogen are found, the establishment of markets is likely to develop over time, depending upon the relative locations of production and demand. Initially, markets might be local or regional to the source, expanding to national or international as volume production and infrastructure develop.

### 4.2.1 Local, regional and industrial grouping market models

For small-scale or remote natural hydrogen reserves, or sites that begin production before extensive infrastructure is in place, localised markets present an important opportunity to serve nearby or off-grid customers who can benefit from direct access to hydrogen without the need for extensive transport infrastructure. In remote or isolated areas, such as rural communities, industrial sites, or isolated infrastructure, natural hydrogen could provide a cost-effective and low-carbon energy solution. By meeting local demand directly, these markets reduce the costs and complexities associated with importing energy.

For example, the Monzón Field in Spain is projected to hold recoverable volumes of hydrogen, with plans to produce hydrogen to supply local industrial demand by the end of the decade. If realised, this would highlight natural hydrogen's promise as a low-cost, low-carbon resource, tailored for a decentralised market where energy can be used locally without extensive transport infrastructure.

The existence of local markets and ability to valorise hydrogen close to the location of exploration will likely be an important end-use while the market scales up. With its competitive production costs, high energy return on investment, and minimal processing requirements, natural hydrogen has the potential to support the rapid scaling of the hydrogen economy while large-scale renewable infrastructure develops. In the long run, it may be that natural hydrogen will be connected into the planned international trade in low carbon hydrogen.

For natural hydrogen reserves located near industrial clusters or regional hubs, a regional market model could facilitate reliable and economical hydrogen supply to local industries[125]. Industrial users in regions where hydrogen reserves coincide with energy or manufacturing infrastructure can benefit from a clean, low-cost hydrogen supply, supporting decarbonisation across sectors such as steel, ammonia production, or refining. By supplying industrial clusters directly, this model enhances energy security, reduces transport costs, and aligns with growing regional energy policies and carbon reduction targets. Establishing dedicated infrastructure to transport hydrogen within industrial zones or nearby cities also enables flexible hydrogen distribution and easier integration with existing industrial operations, creating a model for regional resilience and energy independence.

An example of such regional scale concentrated industrial hubs for natural hydrogen resource includes the mining industry. The mining industry accounts for a large percentage of GDP in many nations. For Canada and Australia, as two major examples, the industry accounts for between $20 – 50 billion in total value per year[146, 147, 148]. This has increased steadily over the past 20 years especially as conventional metals (gold, silver, copper, zinc) have expanded to include diamonds. Further increases are occuring due to the search for critical minerals required for electric vehicles (eg nickel, lithium). There are two key points that connect this major economic activity to the question of natural hydrogen:

- **Geologic co-location**
  In areas such as Ontario, Quebec and Western Australia major concentrations of mining activity is focused on the same rocks that produce hydrogen (ultramafic, mafic, iron-bearing formations).
- **Mines are heavily concentrated in localised areas**
  (dozens in the Sudbury-Timmins-Kirkland Lake corridor in Ontario; a similar high concentration in the Abititi-Temiskaming corridor in Quebec; 50 – 100 mines across Western Australia). Similar concentrations can be identified throughout the world including the southern hemisphere, Scandinavia and the Russian Federation.

As such the mining sector presents concentrated industrial bases, co-located with geologic settings of high hydrogen production potential, and to some degree in areas otherwise isolated from urban based industry and power production (eg the diamond mines of Canada's Northwest Territories). Local power generation in such highly concentrated industrial corridors could be a net economic benefit, as well as a boost to decarbonisation of mining activity.

### 4.2.2 National and international markets

If large-scale reserves are identified, or if natural hydrogen production proves economically scalable, there is potential to integrate these reserves into national, or even international hydrogen markets and transport and storage infrastructure that is under development for other colours of hydrogen. Strategically located reserves could support broader hydrogen trade by connecting to planned or existing pipeline networks, hydrogen storage facilities, or transportation ports, allowing hydrogen to reach distant markets. International export could be feasible in the form of hydrogen derivatives like ammonia or methanol, which are easier to ship over long distances. However, entering the national or international markets would require significant infrastructure investment and planning, such as the development of pipelines, ports, and storage facilities. In this model, natural hydrogen could contribute to cross-border hydrogen flows and global supply chains, complementing the growing trade in green and blue hydrogen and potentially serving as an export commodity for hydrogen-rich countries.

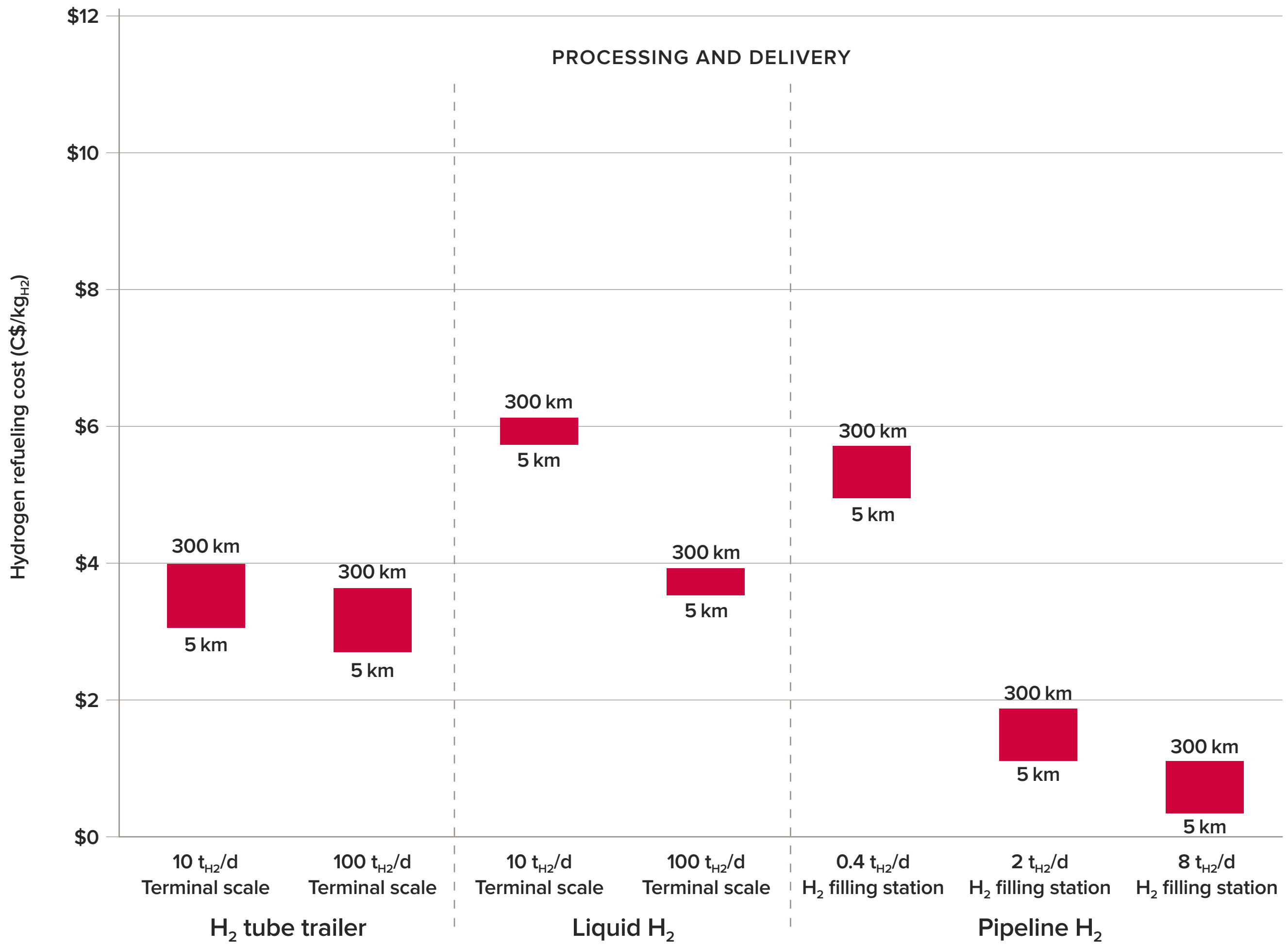
As global hydrogen demand continues to rise, long-distance hydrogen trade flows will play a pivotal role in efficiently matching low-cost supply with demand centres. According to the Hydrogen Council's *Global Hydrogen Flows* report[149], approximately 400 million tons of hydrogen will be transported over long distances by 2050, with 190 million tons crossing international borders. This includes hydrogen and derivatives like ammonia, which are likely to dominate maritime trade. By 2050, a mature hydrogen market is expected to emerge with key trade routes with hydrogen being produced and piped as gas, or converted to ammonia or other synthetic fuels for shipment around the world. For natural hydrogen to integrate into this global market, local reserves with sufficient scale could potentially connect to planned pipeline infrastructure or, where feasible, convert hydrogen to transportable derivatives.

As a low-density gas, the delivery costs for hydrogen are high and vary according to maturity of market, distance and volume of gas being moved. Within Alberta, Canada[150], explored the cost of transporting green and blue hydrogen. While the co-location of hydrogen producing geologic settings with regional concentrated industry hubs might mean the transportation distances would be less for natural hydrogen's initial markets, it is nonetheless informative to examine Khan's analysis. With distances in Canada and other countries the economics indicate the need for proximity to markets. Khan[150] investigated the techno-economics of three hydrogen transportation modes (1) compressed hydrogen in tube trailers (TT) trucked to stations, (2) liquid hydrogen ($LH_2$) in cryogenic tanks trucked to stations, and (3) compressed hydrogen in pipelines to the station (Figure 7).

Khan *et al*.[150] observed if volumes are small (eg early stages of the hydrogen economy) it is feasible to consider that transport via compressed hydrogen delivery using tube trailers. For small volumes this makes the most sense also for short distances, at a cost of (2.2 – 2.92 $/kgH_2$). Liquid hydrogen delivery is more attractive for distances over 300 km, but delivery costs with these supply chains is estimated to be (2.2 – 4.4 $/kgH_2$). If the volume is great or it is a mature market then a dedicated pipeline may be an option, which for a large volume of ≥2 tonnes hydrogen per day the delivery costs could be as low as (<0.73$/kgH2). Pipeline costs of a similar magnitude are proposed by Parker in other studies[151, 152, 153]. In the Thunder Said Energy (TSE) study (Figure 8), the costs and the complexities of cryogenic trucks, and chemical hydrogen (eg ammonia in an LPG tanker) carriers were also examined[153]. TSE concluded that the Midstream costs for $H_2$ will be 2 – 10 times higher than comparable gas value chains, also that up to 50% of hydrogen's embedded energy may be lost in transportation and conversion back into $H_2$ through ammonia cracking. TSE also looked at the cost of pipelines and found that the cost for new H2 pipelines is 2 times new gas pipelines and 10 times existing gas pipelines, per mcf-equivalent of energy transport. The pipeline requirements for hydrogen and natural gas are compared in Table 3[154].

FIGURE 7

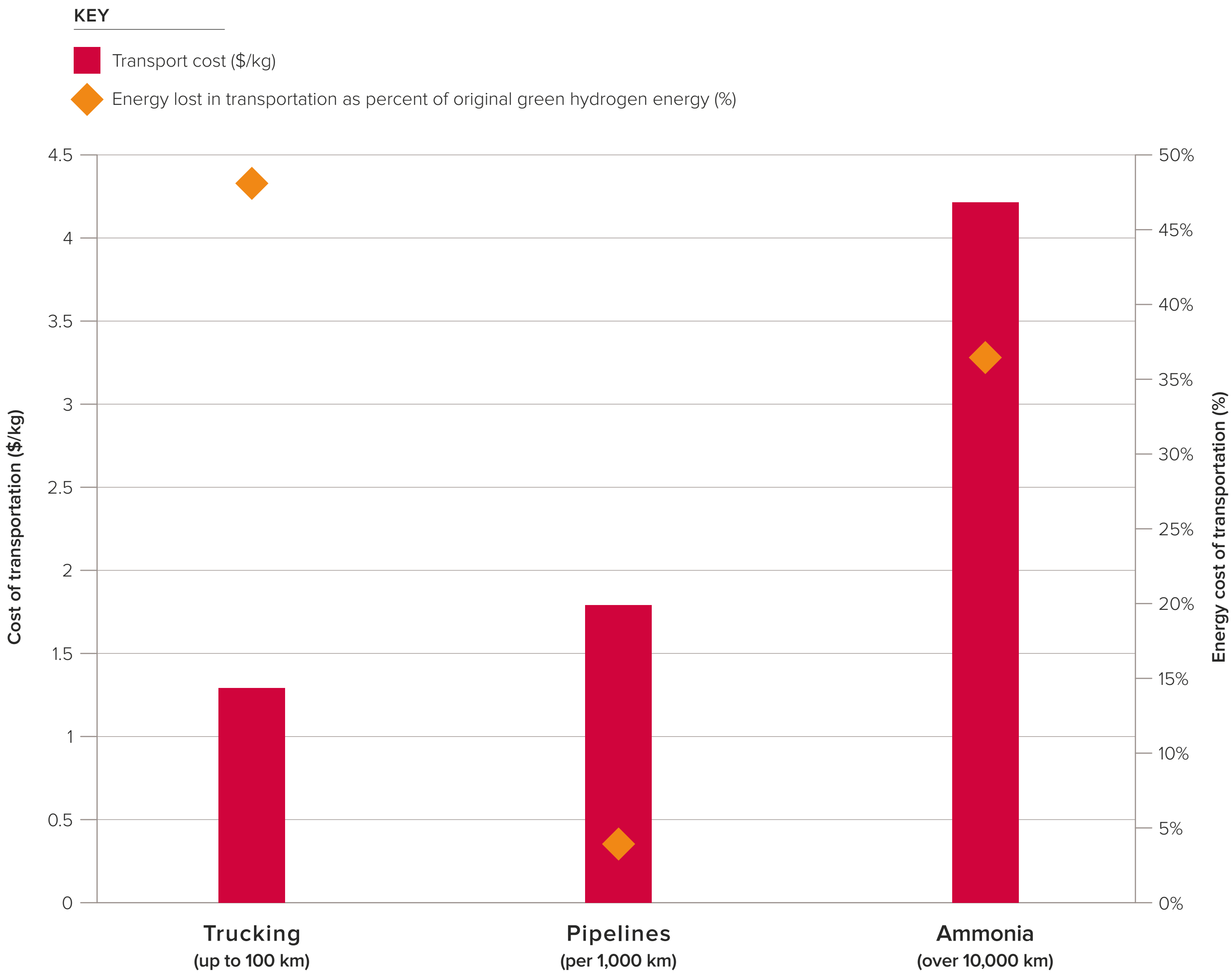
Transport cost of hydrogen (C$/kgH2) for tube trailers, liquid hydrogen and pipeline (for Alberta, Canada)[150].




Note: The analysis assumes use of large transmission pipelines capable of transporting 300 $tH_2$/day over 295 km and 100 $tH_2$/day over 35 km.

FIGURE 8

Transport costs of hydrogen




Source : Thunder Said Energy 2020[153].

TABLE 3

Some key characteristics of hydrogen versus natural gas pipelines[154].

| Indicators | Hydrogen pipelines | Natural gas pipelines |
|---|---|---|
| Volumetric energy density of transported fuel under ambient conditions (MJ/m$^3$) | 12.7 | 40.0 |
| Current total length in the world (km) | >5,209 | >3,200,000 |
| Common diameter of pipes used (cm) | 20 – 66 | 30 – 122 |
| Typical pressure currently used (psi) | 1,000 – 5,000 | 200 – 1,000 |
| Typical thickness of pipes (mm) | | |
| High-pressure pipelines | 10 – 30 | 8 – 20 |
| Low-pressure pipelines | 5 – 15 | 3 – 8 |
| Average energy used for compression from ambient pressure to 500 bad (kWh/kg) | 3 – 10 | 0.3 – 0.8 |
| Average spacing between compressor stations (km) | 10 – 100 | 65 – 200 |

### 4.2.3 Storage of natural hydrogen

The need to store natural hydrogen at source is likely to be small (compared to the post-process storage of blue and green hydrogen), as the underground reservoir is itself the store. If intermediate bulk storage is needed, for example post purification, then salt cavern technology could be used if the geology is favourable. Currently there are four salt cavern storage schemes for pure hydrogen worldwide (three located in Texas, USA[155] and one in Teesside, UK) used to store hydrogen for industrial use or for strategic reserves. Other alternatives under investigation are geological storage in porous rocks either in depleted hydrocarbon fields or saline aquifers.

There are no commercial porous storage facilities globally, but several demonstrators are at various stages of deployment[156], with storage of pure hydrogen having commenced in 2023 at the RAG Underground Sun facility in Gampern, Austria. As for any form of geologic storage, investigations are evaluating potential for induced seismicity, leakage, changes in microbial or geochemical reactions that could lead to the production of hydrogen sulphide gas ('souring')[157, 5, 158]. Subsurface storage repositories can also face legal barriers, and conflicts of interest (for example with other industries) including social license[159].

In addition to these hydrogen specific issues, in common with all underground repositories, the environmental impact of land footprint, ongoing maintenance and monitoring, and decommissioning phases must be accounted for. Social perception of hydrogen and different aspects of its value chain is highly variable, from a positive attitude to hydrogen and its decarbonisation potential in general, to decreasing acceptance when it comes to large-scale infrastructure in the neighbourhood[160].

Although, experience from developing supply chains indicates that in the short-term, storage demand can be met by surface storage in cylinders, this type of storage is relatively expensive and of limited storage capacity when compared to geological storage. It might, however, provide a viable option for more localised storage-use application of hydrogen, close to its source. Storage may not be as important a factor for natural hydrogen as it is for blue and green hydrogen, due to a greater likelihood of use near sites of origin. Storing natural, or any colour of hydrogen will also involve several key considerations including the construction of storage infrastructure, the operational energy use, maintenance, and end-of-life management[157, 158].

# Creating a commercial environment

## 5.1 Financing

Since 2022, the potential to explore and produce hydrogen resources has gained significant media attention. Over 40 new companies have been formed or have announced business activities in the hydrogen sector around the world[161]. Dedicated exploration, drilling, testing, and surveying have commenced, with several exploratory efforts underway in Australia, USA, Spain, France, Albania, Colombia, South Korea and Canada. Although geological surveys have been launched to further evaluate hydrogen potential, most exploration efforts have been spearheaded by private companies. In 2024, investors collectively committed $75 billion to 'clean hydrogen' development across 434 projects worldwide[162]. Natural hydrogen, however, has received relatively little funding (on the scale of hundreds of millions of dollars) due to its nascency. Private investment is similarly at an early stage. Significantly greater public and private funding will be needed for the hydrogen industry to scale. Both venture capital and infrastructure investment models from existing extractive industries (eg mining, oil and gas) should be leveraged. Where hydrogen consumption is in a different location to extraction, cross-border or development financing may also come into play. The capital stack for hydrogen will have to be built across technology-focused venture mandates to support detection and exploration tools; exploration capital, scaled infrastructure and energy equity capital, offtakes, project finance and alternative (eg equipment financing) and mainstream (bank) credit.

Natural hydrogen will have specific funding needs due to the upfront costs of exploration and extraction:

- Capital expenditure may form a greater share of the overall levelised cost of natural hydrogen than for other forms of hydrogen production.
- Risk profiles are likely to be high for early exploration, potentially higher than most commercial mandates would seek for a risk-adjusted return. Catalytic capital such as grant funding, government support or philanthropic or first-loss funding will be required.
- As hydrogen supporting technologies may take longer than a traditional investment cycle (<10 years) to come to maturity, patient capital investment may be required.
- Specific risks also come into play, such as early investment bubbles or misuse of public funds for high-risk exploration.

## 5.2 Markets, regulation and incentives

Although nascent, the natural hydrogen industry is likely to need targeted policy support across its value chain. A comprehensive policy framework might encompass market mechanisms, environmental regulations, regulatory alignment, and strategies for building social acceptance. Key areas include:

- **Market demand and procurement frameworks**
  Establishing a viable market for hydrogen requires effective price discovery mechanisms, such as contracts for difference and advanced market commitments, alongside incentives for early adopters to ensure long-term price stability. Inclusion of hydrogen in national and regional hydrogen strategies would facilitate coordinated development across borders and integrate it with other hydrogen forms. For instance, considering hydrogen in certification schemes, like the UK's low-carbon hydrogen standard, could help recognise its value within a broader low-carbon framework. Lessons from market creation pathways used in other cleantech industries, such as advanced market commitments (carbon removal), power purchase agreements (renewables, next-generation geothermal), and buyers' clubs (renewables) could be powerful tools for pulling in demand.

- **Incentives for research, development, and demonstration**
  Investment in hydrogen-specific technologies, particularly in exploration tools, is critical to attracting private capital and mitigating technical uncertainties. Ongoing support for research and development is necessary to tackle the existing technological and economic challenges within the industry. This is especially important for hydrogen since available data is broadly coincidental and early exploration will carry a high-risk profile.

  Tax incentives could be aligned with the anticipated structure of the capital needed for hydrogen projects. For example, tax incentives could be structured to make a project more investable as it searches for upfront funding. Currently, the UK offers incentives for low-carbon hydrogen through revenue support mechanisms[163]. This type of price adjustment policy could be beneficial for hydrogen, but considering the upfront costs to exploration and potential cost competitiveness of natural hydrogen versus other forms of hydrogen, upfront payments for exploration could be more effective.

- **Streamlining regulatory processes**
  Simplifying permitting and licensing processes is essential to accelerate exploration efforts while maintaining transparency and minimising bureaucratic delays. Regulatory alignment is particularly important for promoting cross-border hydrogen trade and ensuring standardised practices. Anticipating the development of this market and ensuring coordinated developing of natural hydrogen across borders and alongside other generation types of hydrogen. For example, consideration of hydrogen in certification schemes that reward low-carbon production (such as the UK's low-carbon hydrogen standard[139]) would be valuable. The production of natural hydrogen is not necessarily zero emissions. Comprehensive environmental regulations to address the potential risks associated with hydrogen extraction (eg groundwater protection, land use, embedded emissions and transportation) will be critical to underpinning these standards. International regulatory alignment will be important to promote cross-border hydrogen trade and standardisation.

## 5.3 Permitting natural hydrogen exploration and development

Several countries are starting to address the licensing of natural hydrogen exploration, recognising its potential as a low-carbon energy source. In Southern Australia, the government amended the Energy Resources Regulations 2013. These amendments classified hydrogen, hydrogen compounds, and by-products from hydrogen production, as regulated substances under the Energy Resources Act 2000 (ER Act)[164]. As a result, companies can now apply for a Petroleum Exploration License (PEL) to explore for natural hydrogen, and the transmission of hydrogen or hydrogen compounds is permitted under the transmission pipeline licensing provisions of the ER Act. Some of the Canadian provinces that have acted on this issue to date have addressed hydrogen permits and leases using the processes as for helium, which falls under the Oil and Gas Registry Regulations (OGTRR)[165] . France has also introduced regulations that allow companies to apply for exclusive research or exploration permits for natural hydrogen. This legal framework makes it one of the first European countries to officially recognise and regulate natural hydrogen exploration.

The Petroleum Resources Management System (PRMS) is a globally recognised framework developed by the Society of Petroleum Engineers (SPE) that provides guidelines for evaluating and reporting the quantity of petroleum (oil and gas) that can be recovered from a reservoir, under varying levels of certainty. The system is used to assess both technical and commercial factors to help standardise how resources and reserves are defined and reported. In August 2022 the SPE Oil and Gas Reserves Committee (OGRC) advised that the principles of the PRMS can be extended to substances other than hydrocarbons, including the gaseous extraction of carbon dioxide, helium and hydrogen[166].

In the UK, a specific regulatory framework for natural hydrogen exploration is not yet fully established. Following conventional exploration pathways, natural hydrogen would require an area specific exploration and development license, planning permission for onshore drilling along with the relevant environmental permits and Health and Safety Executive (HSE) oversight for well design and operational safety.

Natural hydrogen is not yet explicitly recognised in the UK's energy resource regulations as a 'regulated substance'. The North Sea Transition Authority (NSTA) does not yet have the remit to license hydrogen exploration. Consequently, companies interested in exploring for natural hydrogen may need to follow frameworks established for oil and gas. This involves the issuing of a Petroleum Exploration and Development License (PEDL) from the NSTA. This license grants companies the right to explore for petroleum within specific areas. However, there is no direct inclusion of natural hydrogen under this license yet, though some companies might use this route if geological conditions suggest natural hydrogen potential in petroleum-bearing formations.

Another pathway being explored is through geothermal licensing, which involves similar subsurface geological exploration methods. Some geological formations that are suitable for geothermal energy might also produce natural hydrogen, although hydrogen is not currently a recognised resource in geothermal legislation.

For hydrogen exploration to become formally regulated, the Department for Energy Security and Net Zero (DESNZ) would require robust evidence to justify a policy change. In the interim, initial onshore developments will likely be managed under local planning processes, requiring environmental assessments and community consultations. If hydrogen production from certain formations is likely to yield methane (such as from organic material maturation), the project may fall under existing hydrocarbon licensing. Conversely, hydrogen produced from geological processes like serpentinisation is less likely to involve hydrocarbons, which could exempt it from hydrocarbon-related licensing requirements. This differentiation highlights the need for a flexible regulatory approach that accounts for specific hydrogen sources and associated gases.

Beyond licences, any hydrogen exploration or drilling project would need to obtain planning permission, which involves environmental assessments and community consultations. This may be challenging as the full environmental impacts of the risks of hydrogen leakage are not fully known. If community engagement is not well managed even before any exploration project begins, there may be opposition from residents, environmental groups, or local governments which could delay the approval process or result in additional conditions being placed on the project, potentially increasing costs and timelines. Hydrogen exploration would also require permits under environmental regulations. This will include environmental permits from Environment Agency in England, the Scottish Environment Protection Agency (SEPA) in Scotland, Natural Resources Wales (NRW) in Wales, or the Northern Ireland Environment Agency (NIEA). Hydrogen is highly flammable, and its leakage could pose a risk. HSE will need to be assured that drilling and transmission operations will not pose safety hazards to workers, nearby communities and the environment.

Successfully navigating these licensing and planning challenges requires a well-prepared strategy that anticipates technical, environmental, and community concerns while ensuring compliance with the evolving regulatory landscape in the UK. Community engagement will be critical, as opposition from residents, environmental groups, or local governments could result in additional conditions or delays that may increase project costs and timelines.

## 5.4 Social license to operate

The successful deployment of hydrogen technologies depends not just on their technical feasibility but also on social acceptance. If residents in communities impacted by hydrogen development are excluded from decision-making processes[167], scepticism about the intent of transitioning to cleaner energy sources may arise. Given historical discrimination, communities rightfully express concerns over health, safety, environmental impacts, and the potential perpetuation of fossil fuel industries.
While public sentiment toward hydrogen technologies has generally been neutral to positive[168], the concept of geological hydrogen remains novel and under-discussed. To promote social acceptance, early projects need to create a good track record, where stakeholders prioritise community engagement, transparency, and benefit-sharing mechanisms. By ensuring community voices are central to hydrogen initiatives, the industry can foster trust, enhance acceptance, and support a more equitable energy future.

### 5.4.1 Community engagement

Effective community engagement is critical for fostering social acceptance and participation in hydrogen initiatives. Policymakers must prioritise early and ongoing interactions with local communities to build trust and address concerns. This could involve organising workshops and seminars, setting up citizen panels and public hearings and collaboration with local organisations. Educational events can provide communities with essential knowledge about hydrogen technologies and their implications, helping dispel myths and alleviate fears. Community members often prefer to engage with developers through structured formats like citizen panels and public hearings[169]. Such measures facilitate transparent dialogues between stakeholders and the community. Involving local civic society organisations and representatives can help tailor messages and outreach strategies to resonate with community values and concerns, ensuring that all voices are heard.

### 5.4.2 Transparency and public awareness

To cultivate a well-informed public, it is vital to ensure transparency in communication about the risks and benefits associated with hydrogen projects. Key strategies include publishing open-source data and sharing accessible data regarding environmental impacts, safety protocols, and project progress, that can empower communities to make informed decisions. Further, conducting objective assessments can be effective, engaging independent experts to conduct fair evaluations of the environmental and social impacts of hydrogen technologies to enhance credibility and foster community trust.

### 5.4.3 Benefit-sharing mechanisms

Establishing benefit-sharing mechanisms can further promote social acceptance by ensuring that local communities receive tangible benefits from hydrogen projects. Strategies might involve:

- **Promoting local consumption**
  Prioritising local sourcing and minimising transportation distances can help ensure that the economic benefits of hydrogen production remain within the community.

- **Shareholding communities**
  Allowing local communities to be shareholders in hydrogen projects can create a sense of ownership and shared responsibility, reinforcing the idea that these initiatives serve community interests.

- **Royalties and Revenue Sharing**
  Implementing systems for sharing project revenues or royalties with local communities can provide direct financial incentives, making it clear that they are beneficiaries of local developments.

Figure 9 summarises the steps, challenges, frameworks and enabling actions that are discussed above to successfully develop a commercially viable natural hydrogen industry.

FIGURE 9

Developing a commercially viable natural hydrogen industry

**ENABLING FRAMEWORKS**

- **Social acceptance:** Best practise for community engagement and environmental monitoring
- **Policy drivers:** Subsidies, incentives, carbon pricing
- **Financing and investment:** Innovative funding models to de-risk early-stage projects
- **Technology R&D:** Across all aspects of the value chain
- **Skills development:** Across all aspects of the value chain

| | Geological source to accumulation | Production and extraction | Surface processing and storage | Transportation and distribution | End use markets |
|---|---|---|---|---|---|
| **STEPS** | Geological source to accumulation | Production and extraction | Surface processing and storage | Transportation and distribution | End use markets |
| **CHALLENGES** | Resource estimation uncertainty<br>Hydrogen production window<br>Dynamics or hydrogen systems<br>Exoloration technologies | $H_2$ well Integrity standards<br>$H_2$ material compatibility<br>$H_2$ purity and associated gases<br>Uncertainty in flow dynamics | Transporting $H_2$ at pressure<br>Gas separation/ dehydration<br>Fugitive emissions<br>Buffer storage if necessary | Local/regional use vs transport<br>Pipeline compatibility<br>Compression costs<br>Tube trailer capacity/ costs<br>Fugitive emissions | Production cost uncertainty<br>Infrastructure gaps<br>Purity requirements<br>Market uncertainty |
| **ENABLERS** | Hydrogen play clarity<br>Advanced geophysical methods<br>Integration of noble gas tracers<br>Improved hydrogen sensors | Hydrogen-resistant materlals<br>Enhanced hydrogen well design<br>Improved hydrogen monitoring | Hydrogen ready certification<br>Long duration durability testing<br>Gas separation membranes<br>Advanced leak detection system | Hydrogen resistant materials<br>Improved tube trailer capacity<br>Hydrogen ready certification<br>Improved $H_2$ compression | Policy drivers for natural $H_2$<br>Market incentives<br>Decentralised hydrogen hubs<br>Integration into sectors |

**REGULATION**

Exploration Licencing → Production permitting → Environmental impacts and planning →

**ENABLERS**

- Mapping and addressing regulatory barriers
- Development of streamlined permitting processes
- Integration of hydrogen-specific environmental assessment
- Training or relevant stakeholders

# Conclusions

Natural hydrogen shows increasing potential as a key addition to the portfolio of hydrogen production methods. Hydrogen has a wide range of potential applications, including the decarbonisation of foundation industries, use in renewable energy storage and as a means of fuelling, for example aircraft, heavy goods vehicles and off-road vehicles. Extraction and henceforth application of natural hydrogen hinges on more fundamental exercises including exploration and mapping.

## Key conclusions

Natural hydrogen's formation within the Earth's crust through well-understood geochemical reactions is a phenomenon well-documented worldwide for many decades. These processes include serpentinisation and other chemical reactions with iron-rich rock as well as radiolysis. The geochemical processes driving natural hydrogen formation, although well-understood, still leave open questions regarding the best conditions for large-scale production. Most deposits of commercially viable natural hydrogen are found in the continental crust in a wide range of rock types. Although large volcanic sources of hydrogen exist globally, these areas are usually not practical for commercial extraction. Coupling hydrogen data with noble gas tracers suggests there is little evidence to support claims of long-term renewal of hydrogen sources, or of 'deep sources' migrating from the mantle or core.

Efforts to map natural hydrogen's presence worldwide have been largely empirical, leaving significant gaps in understanding its full potential. Therefore, there may be many 'false negatives', eg locations where no hydrogen is reported, because it has not been looked for or where hydrogen was never analysed. Meanwhile for many countries, including the UK, no databases or maps currently exist.

Efforts are currently underway around the world to produce maps of natural hydrogen potential by integrating reported occurrences with lithology and mineralogy, structural and trapping features, and geophysical data[33, 34, 46]. Some quantitative estimates of hydrogen exist on a planetary scale and are large enough that even capturing a small proportion for commercial use could enable natural hydrogen to play a significant role in the coming years. However, specific estimates of commercial potential are limited by uncertainties regarding hydrogen migration, trapping as well as the relationship between surface seeps and subsurface accumulations. Hydrogen can be consumed underground by chemical reactions with neighbouring rocks or by subsurface microbes. These processes reduce the amount of freely available natural hydrogen for extraction. Just how these microbial ecosystems might be impacted by hydrogen exploration and indeed their role in consuming hydrogen is not well understood. Thorough evaluation and testing are needed to ensure accurate identification of genuine hydrogen sources so as not to confuse these with microbial hydrogen or artifacts from drilling.

## Potential future developments

Value chains and lifecycle analyses for natural hydrogen extraction are still in their early stages, highlighting uncertainties in accessibility, distribution and scalability for widespread use. Compared to green hydrogen, natural hydrogen may require less land and water, and need less energy to power its extraction, purification, transportation and storage. As for green hydrogen, the overall carbon emissions are largely dependent on the electricity sources used for processing ie reduced greenhouse gas emissions will be seen where renewable energy is used for power.

These factors indicate natural hydrogen may show potential for an overall reduced global warming potential when compared against green hydrogen, while also diversifying the global supply of hydrogen. However, its role within the energy transition is not well established. Development of suitable licensing and permitting processes could be critical to establishing a natural hydrogen value chain and thus realising its potential applications. Getting to this stage requires regulatory, legislative and licensing support to drive exploration efforts. It also requires building public trust and engagement to ensure a social license to operate is secured.

Early-stage commercial opportunities may focus on regionally concentrated industrial hubs co-located on the same geologic settings where hydrogen accumulations have most often been found (eg iron-rich or iron-magnesium rich rock already developed for mining of gold, copper, nickel, diamonds or critical minerals). As storage/transport infrastructure for hydrogen of all forms (including manufactured hydrogen) develop on a global scale, natural hydrogen hubs may form part of those larger networks and markets.

## Research needs

While the existence and formation processes of natural hydrogen are well-established, more needs to be understood about its production rates, how it migrates in the subsurface and is trapped, as well as the links between surface seeps and underground reservoirs. Worldwide, researchers are working to better understand these processes and map areas of hydrogen potential using geological and geophysical data. Although the sources and geochemical processes of natural hydrogen are well-understood, the optimal conditions for its production and how it interacts with rocks and microbes that can consume or alter hydrogen, are not.

Although hydrogen can have indirect greenhouse effects, its impact on global warming is significantly lower than methane, especially in terms of short-term climate effects. However, to be considered a truly low-carbon energy source, the removal and sequestration of co-associated contaminant greenhouse gases is necessary, posing additional challenges and costs to the extraction process. Its carbon intensity can be measured under the threshold fixed by the regulator (in Europe: 3.38 kg $CO_2$ / kg $H_2$).

## In summary

Natural hydrogen has the potential to complement other manufactured sources of hydrogen for use in net-zero solution technologies and industry decarbonisation. However, in order to get there, supportive legislation and regulatory frameworks are essential, particularly in the UK where this has not yet been considered, to enable exploration and establish appropriate licensing for extraction.

The scale of potential resource remains uncertain due to the lack of data. Whilst the environmental impacts of extracting natural hydrogen are currently not documented, early indications show the promise of reduced energy, water and land use compared to green hydrogen. Early investment trends indicate that it may at first serve as a regional energy source for industries such as mining, especially where activity is located on geologic settings favourable to hydrogen production. Its use in the growing global hydrogen markets remains unclear.

While still in its infancy, natural hydrogen could become an important clean energy source through a combination of further research, investment and the establishment of supportive policies for exploration and extraction.

## APPENDIX 1

# Glossary of terms

**Anthropogenic**
Originating from human activity, as opposed to from natural processes. (eg Anthropogenic climate change: climate change caused by human activity)

**Anthropogenic timescales**
Timescales relevant to and measurable over human timespans, typically ranging from years to millennia. As opposed to geological timescales, which range from hundreds of thousands to billions of years.

**Basement / crystalline basement**
Old, hard rocks found below the sedimentary layers in which hydrocarbons are typically found, and above the mantle. Usually the oldest (Precambrian) crystalline or recrystalised igneous or metamorphic rocks, forming the middle and lowermost levels of the Earth's crust. See also: crystalline source rock

**Carboniferous**
A geologic period spanning 60 million years, from 359 to 299 million years ago. Carboniferous rock strata are notable for rich coal deposits.

**Clastic rocks**
Sedimentary rocks formed of fragments (clasts) of existing rocks that have been broken down and compacted.

**Connate water**
Water trapped in pores of sedimentary rock when they are formed. Also known as fossil or formation water.

**Contact strata**
Rock layers in contact with one another, marking a boundary between the distinct layers.

**Crystalline source rocks**
Igneous or metamorphic rocks from which hydrogen may be produced. See also: basement.

**Electrolysis**
A process using electricity which splits water ($H_2O$) into hydrogen ($H_2$) and oxygen ($O_2$).

**Gas phase**
A state of matter where substances exist as gases.

**Geological timescale**
Timescales used to represent very long-term timespans, typically spanning hundreds of thousands of years to billions of years, subdivided as epochs, periods, eras and eons.

**$^3He$**
$^3He$ is a primordial isotope of helium that is not produced in significant quantities on Earth. Its abundance relative to hydrogen or other isotopes (like $^4He$) is used as a tracer for mantle-derived volatiles.

**Igneous rocks**
Rocks formed through the cooling and solidification of magma (molten rock).

**Kerogen**
Solid compressed organic matter found in sedimentary rocks.

**Lewisian gneiss**
A suite of Precambrian metamorphic rocks that outcrop in the northwestern part of Scotland

**Lithological**
Relating to rocks and minerals, including their study.

**Mafic**
Igneous rocks that comprise much of the Earth's crust, and are high in magnesium and iron, such as basalt.

**Migration**
The subsurface movement of a fluid or gas through rock, due to the rock's permeability.

**Mineralogy**
The study of minerals.

**Ophiolites**
Sections of the Earth's oceanic crust that have been uplifted and exposed above sea level by tectonic activity. They typically include mafic and ultramafic rock.

**Orthopyroxenes**
Common silicate minerals.

**Peridotite**
A type of igneous rock amenable to serpentinisation and the production of hydrogen.

**Play**
Oil or gas prospects in the same region that are governed by the same set of geological conditions.

**Precambrian crust**
The Earth's crust formed in the Precambrian era, the longest lasting geologic era, dating from 4.6 billion years ago to 541 million years ago. Estimated to comprise 72% of the Earth's continents by area.

**Radiogenic granites**
Granite rocks which produce heat from the decay of natural radioactive material.

**Radiolysis**
The breaking apart of molecules through exposure to ionising radiation. For example, the breaking of water molecules into hydrogen and oxidised chemicals by exposure to naturally occurring radiation in rocks containing radioactive elements such as uranium, thorium and potassium.

**Seal rocks**
Also known as cap rocks, an impermeable layer of rock which prevents the migration of fluids or gasses beyond the reservoir boundary.

**Sedimentary basins**
Depressions in the Earth's crust which, over time, accumulate sediments from rivers and seas that eventually formed sedimentary rocks.

**Sedimentary column**
The vertical composition of sedimentary rock layers in a given area.

**Sedimentary strata**
Distinct layers of sedimentary rock.

**Serpentinisation**
The reaction of mafic and ultramafic rock with water, one product of which is hydrogen.

**Tertiary igneous**
An igneous province found in the western British Isles

**Ultramafic**
Igneous rocks composed of >90% mafic materials. See also: mafic rock.

## APPENDIX 2

# Acknowledgements

### Working Group members

The members of the Working Group involved in this report are listed below. Members acted in an individual and not a representative capacity, and declared any potential conflicts of interest. Members contributed to the project on the basis of their own expertise and good judgement.

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