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Discussion Paper

Geological Hydrogen – An Overlooked Energy Source?

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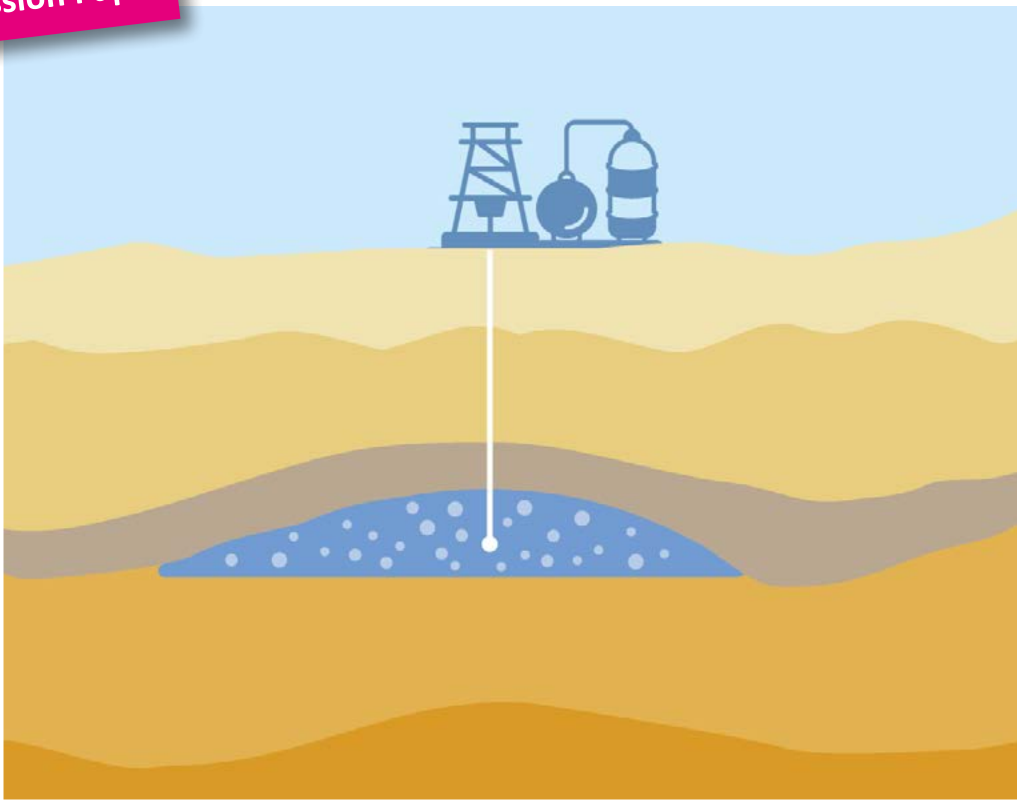
Discussion Paper



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Geological Hydrogen – An Overlooked Energy Source?

Geological hydrogen – what is it?

Geological hydrogen refers to molecular hydrogen occurring in the Earth's subsurface. In the last few years, research interest in this potential resource has strongly increased, and globally over a hundred companies – mostly start-ups – have become involved. Geological hydrogen can be distinguished by whether its generation occurs naturally or is deliberately stimulated.

Natural hydrogen (also white or gold hydrogen) is generated by naturally occurring geological processes without human intervention. It may occur as diffuse seepage or, where geological conditions allow, as subsurface accumulations. Interest increased following the discovery of a natural hydrogen-rich gas in Mali, which was used to supply electricity to a nearby village. This represents the first documented case of sustained hydrogen extraction and use.

Stimulated hydrogen (also orange hydrogen) is produced by deliberately inducing subsurface reactions, for example, through the injection of fluids or catalysts. This concept remains at an early research stage.

Existence of mineable deposits of natural hydrogen uncertain

It has not yet been established whether natural hydrogen occurs in volumes that are economically recoverable at scale, nor whether it can make a meaningful contribution to long-term climate-neutral energy systems. While the geological processes responsible for hydrogen generation are principally understood, significant uncertainties remain regarding its generation rates, migration and accumulation. Hydrogen generating rock types are quite widespread. However, no large, economically viable deposits have yet been confirmed and expert estimates of potential resources vary widely. Elevated hydrogen concentrations alone do not demonstrate the presence of a sustained subsurface accumulation or economically recoverable resource.

Natural hydrogen potentially cheaper than green hydrogen

If economically viable deposits are identified, natural hydrogen could be produced at lower cost than green hydrogen from electrolysis. Under favourable geological and operational conditions, production costs may approach todays cost of grey hydrogen. However, costs will be highly site specific and depend on factors such as drilling depth, flow rate and hydrogen concentration.

Most promising for local and decentralised applications

Most experts view the role of natural hydrogen in the energy transition as complementary rather than transformative, underscoring the need to maintain investment in hydrogen infrastructure and green hydrogen production. Especially in the short and medium term, natural hydrogen might be confined to certain local and decentralised applications. Potential use cases include integration with helium production or geothermal energy projects to diversify revenue streams, as well as local power generation for remote communities or mining operations.

Need for regulatory clarity and targeted research funding

Regulatory frameworks for exploiting natural hydrogen vary significantly across jurisdictions and in the mining codes of most countries, it is not considered at all. Further investment needs clear legislation that facilitates exploration and potential extraction. In addition, targeted public funding for research could help to obtain data for a more secured evaluation of the potentials and generate the scientific evidence needed for informed policy decisions.

Abbreviations

AUD	Australian Dollar
°C	Degrees Celsius
CCS	Carbon (dioxide) capture and storage
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalents
EGS	Enhanced Geothermal System
ESPAS	European Strategy and Policy Analysis System
EU	European Union
EUR	Euro
Fe	Iron
GHG	Greenhouse gas
GWP	Global warming potential
H_2	Molecular hydrogen
H_2O	Water
H_2S	Hydrogen sulfide
He	Helium
IEA	International Energy Agency
kg	Kilogram
km	Kilometre
LCA	Life cycle assessment
LCOH	Levelised cost of hydrogen
m	Metres
MSR	Methane steam reforming
Mt	Megatonne (= 1,000,000 tonnes)
NPV	Net present value
O_2	Molecular oxygen
pH	Measure of acidity/alkalinity (defined as the negative decimal logarithm of proton concentration)
R&D	Research and development
RED III	Renewable Energy Directive III
t	Tonne
TEA	Techno-economic analysis
TRL	Technology readiness level
U.S.	United States
USA	United States of America
USD	United States dollar

Glossary

Abiotic	Processes or materials that occur without the involvement of living organisms.
Adsorption	A process in which molecules from a gas or liquid attach to the surface of a solid material
Biofouling	The undesired colonisation of surfaces by biological organisms, leading to reduced efficiency, blockage, corrosion, or increased maintenance requirements.
Blue hydrogen	Hydrogen produced by methane steam reforming, with the resulting CO_2 captured and stored underground (CCS).
Brown field exploration	Refers to exploration activities conducted in areas with existing mines or resource deposits. They are usually regions with existing infrastructure or prior geological data, reducing technical and economic risk compared to new areas.
Carrier	Structures and fluids through which hydrogen can migrate away from the source rock, including permeable sediments or rock fractures.
CCS – Carbon capture and storage	A process in which CO_2 emitted from energy or industrial facilities, is captured and stored underground. Storage sites are often depleted oil and gas reservoirs and deep lying saltwater aquifers.
CO_2e – CO_2 equivalents	A standardised unit of measurement to compare the effects of different greenhouse gases. This is expressed in equivalents of the greenhouse gas effect of CO_2 over a specified time period.
Cryogenic fractional distillation	A specific method of cryogenic separation used to separate gas mixtures, such as air or natural gas, by cooling them to very low temperatures until they condense and then distilling the components according to their different boiling points.
Cryogenic separation	A gas separation approach that uses extremely low temperatures to liquefy gas mixtures and separate their components based on physical properties such as boiling points.
Crystalline rock	A rock consisting entirely of mineral crystals that grew together during solidification of molten material or metamorphic recrystallization, forming an interlocking mosaic texture. The term is textural and most commonly applies to igneous and metamorphic rocks.
Deposit	A naturally occurring accumulation of material in the subsurface.
EGS – Enhanced geothermal systems	Technology for extracting geothermal energy that use stimulation methods to create or enhance permeability in hot underground rock to enable heat extraction for energy production. Unlike conventional geothermal systems, EGS do not require naturally permeable reservoirs.
Elastomers	Natural or synthetic rubber-like solids with elastic properties.
Electrolysis	A chemical process in which an electric current is used to drive a non-spontaneous chemical reaction, such as splitting water into hydrogen and oxygen.
EU taxonomy	The European Union's sustainable finance classification system established by regulation (EU) 2020/852 of the European Parliament and of the Council. It defines a science-based framework for identifying economic activities that can be considered environmentally sustainable by requiring that activities make a substantial contribution to one or more of six environmental objectives, do no significant harm to the remaining objectives, and meet minimum safeguards.
Exothermic	Describes a chemical or physical process that releases heat into its surroundings.
Flow rate	Volume or mass flow per unit of time.
Flux rate	The amount of a substance, energy or quantity that passes through a given surface, area or system per unit of time. Flux rate measures the speed or intensity of flow.
Gas chromatography	An analytical technique that separates and identifies the components of a gas mixture by passing it through a long, narrow column which inner surface temporarily retains different substances to different degrees, causing them to move through the column at different speeds.

Geological hydrogen	Hydrogen generated or occurring within the Earth's subsurface through geological processes such as water-rock reactions. The term includes both natural hydrogen as well as stimulated hydrogen.
GWP – Global warming potential (100 years/20 years)	A measure that compares the climate impact of different greenhouse gases by expressing their heat-trapping effect relative to CO_2 over a defined time horizon. Commonly used are the GWP100 over a hundred years and GWP20 over 20 years.
Green hydrogen	Hydrogen produced using renewable energy. In most cases, this is done using wind or solar energy to power electrolysis. During electrolysis, water is split into oxygen and hydrogen, requiring large amounts of energy. Green hydrogen production has no direct carbon emissions.
Grey hydrogen	Hydrogen produced from natural gas, primarily through methane steam reforming. Unlike blue hydrogen, the resulting CO_2 is not captured but is released into the atmosphere, resulting in carbon emissions. Most of the global hydrogen production nowadays is produced by this method.
High alloy steel	Steel containing significant proportions of alloying elements, exceeding 5 per cent and often more than 10 per cent of the total composition. Common alloying elements include chromium, nickel and molybdenum. High alloy steels provide improved resistance to corrosion, high temperatures, and hydrogen-related material degradation.
Hot dry rock geothermal energy	Geothermal energy won from hot dry rock, a type of abnormally hot rock that contains little to no water, requiring the drilling of deep wells and hydraulic or explosive fracturing to enable water circulation for heat exchange.
Hydration	A process in which water is incorporated into a material or mineral, changing its composition and physical properties.
Hydraulic fracturing ("fracking")	A well stimulation technique used in energy production in which pressurised fluids and additives such as sand are injected into underground rock formations to create or enlarge fractures, increasing permeability and enabling the extraction of subsurface fluids.
Hydrocarbons	In chemistry, hydrocarbons are defined as organic compounds that are composed entirely of hydrogen and carbon. They are the primary constituent of fossil fuels such as petroleum and natural gas. In a wider sense, the term is also commonly applied to natural gas and petroleum, for example "hydrocarbon exploration", although they do contain small amounts of other elements. The term is used in this wider sense in this paper.
Hydrogen seeps	Places where hydrogen naturally migrates from the subsurface and escapes at or near the Earth's surface into the atmosphere.
Hydrogen system	Geological setting which allows hydrogen to be generated and preserved. The elements include a source rock, a trap structure formed by a reservoir and a seal, and a migration path for the hydrogen to migrate from the source rock to the trap.
Indirect emissions	Emissions associated with upstream or downstream processes such as energy supply, material production or transport, rather than from the activity itself.
Inert gas	Gases such as helium or argon that are not, or only weakly, chemically reactive under normal conditions. They are commonly used to prevent unwanted reactions, for example, in certain laboratory or manufacturing processes.
In-situ separation	A process in which components of a (fluid) mixture are separated directly within the operational environment, such as subsurface or production environment, rather than after extraction, to selectively recover specific substances.
Kerogen	Solid organic material found in sedimentary rocks, derived from various kinds of organic matter such as plants, algae, and microorganisms formed through geological processes. Kerogen is the precursor to oil and natural gas, generating them when heated over geological time.
LCA - Life cycle assessment	A standardised method for assessing the environmental impacts of a product, service, or process across its entire life cycle. This includes stages such as raw material extraction, production, use and recycling or final disposal. The methodology is defined in ISO 14040 and ISO 14044.

LCOH – Levelised cost of hydrogen	An economic metric measuring the average unit cost of producing hydrogen, usually expressed in cost per kilogram, over the operational lifespan of a production facility. It serves as a standardised benchmark cost to compare the cost of different forms of hydrogen production (green, blue, white, etc.)
Liquefied hydrogen	Hydrogen that is maintained in its liquid state by cooling to extremely low temperatures, below -253°C at atmospheric pressure. Liquid hydrogen is roughly 850 times more compact than gaseous hydrogen, which facilitates long-term storage and long-distance transport.
Lithology	Refers to the physical characterisation of rocks, including mineral composition, colour, grain size, and texture.
Membrane separation	A separation process in which selective membranes allow certain components of a gas or liquid mixture to pass through more readily than others, enabling separation.
Methane pyrolysis	A hydrogen production method that converts methane into hydrogen while producing solid carbon instead of carbon dioxide.
Mid-ocean ridges	Underwater mountain ridges formed along the limits of separating tectonic plates, often involving magmatism. Together, the mid-ocean ridges form the longest connected mountain range on the planet, stretching nearly 65,000 km.
MSR – Methane steam reforming	A chemical process in which methane reacts with steam at high temperature to produce a gas consisting of hydrogen and carbon monoxide (also called synthesis gas).
Natural hydrogen	Molecular hydrogen which forms naturally in the geological underground by geochemical processes without human intervention (also referred to as white or gold hydrogen). The term as applied in this paper does not include hydrogen produced by subsurface microbes.
NPV – Net present value	A measure of an investment's value that adds up all expected future cash flows, discounted to today's value, and subtracts the initial investment cost.
Precambrian rock	Rock formed before the Cambrian period, more than 540 million years ago.
Pressure- and temperature-swing adsorption	Two related gas separation methods based on selective adsorption in which specific gas components preferentially adsorb onto solid materials, thereby separating them from the gas mixture, and are then desorbed by changing pressure (pressure-swing adsorption) or temperature (temperature-swing adsorption).
Radiolysis	A process whereby water is split into hydrogen and oxygen (O_2) by the radiation produced during radioactive decay.
Renewable energy quotas	Regulatory requirements that mandate a minimum share or amount of energy to be produced from renewable sources within a defined energy system or market.
Renewable resource	A resource that replenishes at least as quickly as it is consumed and therefore does not become depleted.
Reserve	Reserves are the part of known resources that are demonstrated to be economically recoverable under current technical, market, and regulatory conditions.
Reservoir	A subsurface rock formation with sufficient pore space and permeability to allow the accumulation and flow of gases or liquids. A reservoir can only host hydrogen (or hydrocarbon etc.) accumulations if it is part of a trap structure that is overlain by a seal that prevents the fluids and gases from escaping.
Resource	In geology, resources include all discovered quantities of a substance that could potentially at some point be extracted, regardless of current profitability. Unlike reserves, resources are not necessarily economically recoverable under current technical, market, or regulatory conditions. They may become viable in the future if prices increase, technology improves, or new infrastructure is developed.
Seal	A cap rock with low permeability that creates a barrier which prevents gases and fluids from escaping from an underlying reservoir.

Sedimentary basin	A regional-scale long-lived depression in the Earth's crust where sediments accumulate over millions of years. With continued deposition, underlying sediments are subject to increasing pressure and start compacting, eventually transforming into sedimentary rock. Sedimentary basins host the majority of the world's energy resources, key mineral deposits, and extensive groundwater aquifers.
Sedimentary rock	Rock formed by sediment, such as sand, mud, or organic matter, that are deposited, compacted, and cemented over time, typically at or near the Earth's surface.
Serpentinisation	A water–rock reaction in which primary ferromagnesian minerals (such as olivine and pyroxene) are hydrated and transformed into serpentine minerals, typically accompanied by the formation of magnetite and the release of hydrogen. The process occurs predominantly in ultramafic rocks.
Source rock	In geologic hydrogen systems, source rock refers to a rock that can generate hydrogen through processes such as radiolysis or serpentinisation.
Stimulated geological hydrogen	Hydrogen generated by deliberately enhancing natural subsurface reactions through the injection of fluids (such as water) and, in some concepts, catalytic substances to promote hydrogen production. (also referred to as orange hydrogen).
TEA – Techno-economic analysis	An evaluation that considers technical and economic aspects to determine overall costs and economic outcomes.
Trap	geological structural configuration/geometry that enables the accumulation of fluids. It typically includes a porous reservoir and a low-permeable/ impermeable seal. A trap may form via structural deformation (folds and faults) or variations in the layering of rocks or a combination of both.
TRL – Technology readiness level	A scale of 1 to 9 expressing the level of maturity of a new technology's development. Used to estimate time until market readiness.
White hydrogen	See natural hydrogen

1 Introduction

For the transition toward a climate-neutral energy system and industry, large quantities of low-carbon molecular hydrogen (H_2) will be required. With the development of low-carbon sources of “green” and “blue” hydrogen taking more time than initially hoped, another form of hydrogen has gained increasing attention in recent years: so-called geological hydrogen. It encompasses two forms: the first form of natural hydrogen (or white/golden hydrogen) refers to molecular hydrogen of geological origin formed by natural geological processes. The second form is stimulated hydrogen (or orange hydrogen), where one tries to artificially induce the natural formation of hydrogen in the underground through the injection of substances such as water or catalysts. The primary focus of this paper is on natural hydrogen, but stimulated hydrogen is also addressed where relevant.

Interest in natural hydrogen was largely triggered by the discovery of a hydrogen accumulation in Mali, which became the first known site where natural hydrogen was extracted and used for electricity production for a village. [1] The utilization demonstrates both the existence and practical usability of such deposits.

Since then, scientific publications on natural hydrogen for economic exploitation have increased significantly, and both start-ups and major energy companies have begun exploring its potential. While the topic is increasingly discussed within the geosciences, it has so far received comparatively little attention from experts in energy technology, energy systems analysis, and energy economics. Public awareness remains limited as well.

Nonetheless, political decision-makers in several countries have expressed high expectations regarding natural hydrogen as a future energy resource. Exploration licences have already been granted in several countries including France, Spain, Finland, the USA, Canada, Australia, China and Russia. [1; 2] At the European level, the European Strategy and Policy Analysis System (ESPAS) states in its Global Trends Report 2024 that “the possibility of mining natural hydrogen deposits has potential for a future energy revolution.” [3, p. 28] In Germany, however, natural hydrogen has so far attracted relatively little attention in both policy and research.

This paper aims to provide an overview of the current state of scientific knowledge on geological hydrogen, identify key uncertainties, and assess the potential role of natural hydrogen in the transition of the energy system and industry. We analyse technical, economic, and institutional barriers to development and discuss policy options to advance research and development as well as to create enabling regulatory frameworks, with a particular focus on Germany.

The findings of this paper are based on interviews and a workshop with international experts supported by a literature review. A list of the experts interviewed can be found in the appendix.

2 Geoscience and exploration: Where to look for natural hydrogen?

To date, there is only one case where natural hydrogen has been extracted and used, a facility situated near the village Bourakébougou in Mali (see Infobox p. 16). Apart from that, no economically viable, exploitable deposit of natural hydrogen has been discovered yet, and the knowledge about potential hydrogen accumulations is still very limited.

The existence of naturally occurring hydrogen in the subsurface has been known for over a hundred years. [4] Data on underground hydrogen has been collected for many decades with the objective to analyse subsurface microbiological ecosystems and the role of hydrogen therein. [5] But underground hydrogen was not considered as a potential resource for human use, and there were no dedicated exploration efforts targeted at hydrogen. Many reported occurrences were chance discoveries during hydrocarbon exploration and production, mining and well drilling. In many cases the hydrogen concentration is low, but occasional finds with measured concentrations of over 40 per cent, in some cases even over 90 per cent, have been reported from various regions, including Albania, Australia, Canada, Finland and the USA. [4] Nitrogen, helium, and methane are common components of the remainder gas.

While measured hydrogen concentrations have been reported for many locations, there is little information about the associated hydrogen quantities in the subsurface. In some cases, flow rates of seeps to the surface are reported, but so far, there are no flow tests from wells, which would be required to estimate the hydrogen volume and potential economic viability of a deposit.

To assess if and where potentially extractable deposits exist, it is crucial to understand how natural hydrogen is generated, how it migrates through the subsurface, how it can accumulate in reservoirs, and whether it is consumed by chemical reactions or microbes on the way to the reservoir or in the reservoir itself. This chapter summarises the current state of knowledge for readers without a background in geosciences. A more detailed overview of the geoscientific literature is provided in the appendix.

2.1 Generation and accumulation of natural hydrogen

There are several processes that generate hydrogen underground, but only some of them seem relevant to the potential formation of exploitable deposits. Two processes are considered promising by most experts:

- Reactions of certain types of iron-rich rock with water, such as serpentinisation
- The splitting of water into hydrogen and oxygen by the radiation produced by radioactive decay, referred to as radiolysis

Appendix A.1 gives a more extensive overview of natural hydrogen generation processes. Although the relevant processes of hydrogen generation are in principle understood, high uncertainty remains regarding how much and how quickly hydrogen is generated, and where.

Being a very small and reactive molecule, hydrogen is likely to move away from the source rock and be consumed by chemical reactions or microbes. For hydrogen to accumulate, it needs certain geological prerequisites: 1) a suitable reservoir rock with interconnected pore space and 2) a seal consisting of a low-permeability rock type which prevents the hydrogen from escaping. Reservoir and seal must form a trap structure which keeps the hydrogen in place. Hydrogen may exist underground as a free gas or dissolved in water. Due to the small size of hydrogen molecules, rock types which typically work as a seal for natural gas may not work for hydrogen. Since hydrogen can potentially migrate a long distance, for example along fractures or aquifers, accumulations may be located at a considerable distance from the source rock.

Especially in shallow reservoirs, consumption of the hydrogen by microbes may be a significant issue. Microbial activity is strongly dependent on local conditions such as salinity and the availability of nutrients and water, and may therefore vary greatly. At greater depths, temperatures are likely to be too high for the life of hydrogen-consuming microbes, but drilling deeper is more technically demanding and expensive.

Appendix A.2 elaborates in more detail on the migration, accumulation and consumption processes of natural hydrogen and suitable geological settings for hydrogen deposits. Improving the understanding of these processes is essential for identifying promising locations which may host potentially exploitable natural hydrogen accumulations.

2.2 How much natural hydrogen is there?

In the last few years, several estimates of global annual natural hydrogen generation and global annual leakage to the atmosphere by hydrogen seeping to the surface have been published in scientific literature, based on measured natural hydrogen occurrences and/or modelling. These, however, are not reliable indicators of how much natural hydrogen could potentially be recovered. If hydrogen has been trapped and has accumulated over geological time scales, it may be possible to extract more hydrogen annually than is generated. On the other hand, if most of the hydrogen generated does not accumulate in exploitable reservoirs or is rapidly consumed by microbes, the potential for human use may be negligible.

To assess the potential for commercial exploitation, it is essential to know how much hydrogen is trapped in reservoirs. Based on a literature review, the UK Royal Society[1] concludes that to date, this cannot be quantified due to a lack of data. [4] The assessments of our interview partners reflected this uncertainty: Their expectations of the extent to which economically viable natural hydrogen deposits are likely to exist varied widely, ranging from insignificant to a very substantial potential contribution to the future hydrogen economy.

The annual global leakage to the atmosphere is estimated at up to 0.74 million tonnes per year by a working group of the Royal Society. This estimate excludes volcanic gas flux, because it is unlikely to be commercially exploitable. [4] This is a conservative estimate, some estimates by other authors are several orders of magnitude higher but include sources of hydrogen that are more speculative. For a discussion of some recent scientific publications on quantitative estimates, see Appendix A.3.

For comparison: The current global hydrogen demand amounts to around 100 million tonnes per year and is projected to rise to 530 million tonnes per year until 2050 in a net-zero emissions scenario. [6]

1 The Royal Society is a fellowship of scientists and the United Kingdom's national academy of sciences. It gives science-based policy advice to the UK Government and other institutions. A working group of 12 experts analysed the potential of natural hydrogen as a low-carbon energy resource, the results were published in June 2025.

Infobox: Is natural hydrogen renewable?

A renewable resource is defined as one that replenishes at least at the same rate as it is consumed, and thus is not depleted. Whether a resource can be considered as renewable therefore depends both on the generation and consumption rates. **Most experts conclude that natural hydrogen is not renewable on a human timescale, since the known underground hydrogen generation processes such as serpentinisation and radiolysis are much slower than potential industrial-scale human extraction rates.** [4; 7; 8; 9] If large deposits do exist, they would probably have formed over at least thousands of years. For a more detailed discussion, see Appendix A.2.

Water-rock reactions like serpentinisation are not renewable because they irreversibly consume finite reactive minerals (e.g., Fe^{2+}-bearing olivine). Once the parent rock is fully altered, hydrogen production ceases. Sustaining the reaction requires the creation of new reactive surfaces and continued water supply, for example through tectonic activity or fracturing. [8] This will set limits to the refilling of the reservoir, even in conditions where serpentinisation is relatively fast. A recent modelling study of global hydrogen generation and accumulation indicates that the global annual hydrogen production rate which could be regarded as renewable is in the order of 5 million tonnes per year. This would meet less than one per cent of the expected global hydrogen demand in 2050. [10]

It should be pointed out that “renewable” is not the same as “climate-friendly” or “environmentally friendly”, although these terms are sometimes conflated. Although probably not renewable, natural hydrogen has a low climate impact. The Royal Society concludes that on first estimate, natural hydrogen from a high concentration deposit is likely to have a similar or lower carbon footprint than green hydrogen (see section 3.4). [4]

2.3 Known and presumed occurrences of natural hydrogen

The types of rocks that can generate hydrogen are relatively common on all continents. [4] However, the extent to which hydrogen has been measured and finds have been reported differs by region. One reason there is little data on the hydrogen content of underground gases is that in the oil and gas industry, hydrogen is often used as a carrier gas in gas chromatography, so it cannot be measured. Roughly two thirds of the reported occurrences of natural hydrogen collected in recent literature reviews originate from the former Soviet Union, [11] which is likely due to the fact that hydrogen was part of the measurement program of gas accumulations. By contrast, in some countries there is no data published at all. [1]

Hydrogen concentrations of over 80 per cent have been reported in Mali, the United States, Canada, Australia and other countries. [12; 13; 14; 15; 16; 17; 18; 19] Some of our interview partners questioned the reliability of the published data and urged caution in scrutinising how measurements were conducted and interpreted. For example, hydrogen produced in the drilling process may have been mistaken for geological hydrogen (see section 2.4). Some of our interview partners voiced concern that compilations of natural hydrogen occurrences often include data where the provenance is difficult to verify. These include several decades old historical data where the measurement procedures were insufficiently documented, and information by companies, where details are not revealed for confidentiality reasons.

It should also be pointed out that published data on most reported finds is limited to hydrogen concentration, whereas flow rates, flux rates[2], reservoir pressures and total gas volumes are typically unknown. While the published data suggest that natural hydrogen may be more widespread than was previously assumed,

2 The flow rate measures the volumetric flow or mass flow per unit of time (for example, cubic metres or tonnes per hour or year). The flux rate measures the volumetric flow or mass flow per unit of time and per surface area (for example, kilogram per square metre per hour) and is a measure of the intensity of the flow rather than the total amount.

they provide little information on the size, productivity, or economic viability of potentially exploitable accumulations.

Some experts claim that no large hydrogen deposits have been discovered so far simply because there has been limited effort to look for them, and that we have not been targeting the most promising geological settings. One contributing factor is that most research and exploration use records of historical finds of hydrogen as starting points. These were often conducted during oil and gas exploration campaigns. However, several of our interview partners pointed out that geological settings where natural gas and petroleum oil were being explored may not be the most promising location for large hydrogen accumulations. Another limitation may be that research and exploration have so far focussed mostly on potential source rocks and generation, rather than on potential reservoirs. However, as a strategy to look for exploitable natural hydrogen deposits, it may be better to focus on finding geological settings which provide all elements constituting a hydrogen system, including source rock, migration pathways, reservoir and seal (see appendix A.2). Only if all these elements are present can hydrogen accumulate.

Some potential source rocks of hydrogen generation may also contain deposits of valuable minerals such as iron, nickel, cobalt, copper and gold. [4; 5] Hydrogen may therefore frequently occur at or near mining sites, and in fact hundreds of occurrences of hydrogen associated with ore bodies have been reported in the scientific literature. [4; 5; 20] However, hydrogen deposits may in many cases have remained undiscovered because they are at greater depths than mining operations. [21]

There may be substantial natural hydrogen generation in the deep sea, since serpentinisation often occurs along oceanic plate boundaries. [1] However, this marine hydrogen is not accessible with nowadays technology and its extraction is not expected to become technically and commercially feasible in the short and medium term.

In the last few years, research and exploration activities have increased markedly. Sites regarded as potentially promising by researchers and/or exploration companies have been identified in many countries. The map in Figure 1 shows examples of selected projects in Europe and worldwide.

Note that the hydrogen concentrations in gas samples from a field often vary widely and concentrations stated in Figure 1 are maximum values. Thus, the bulk of the measured annual flow rate stated in Figure 1 p. 15 may have been at much lower concentrations.

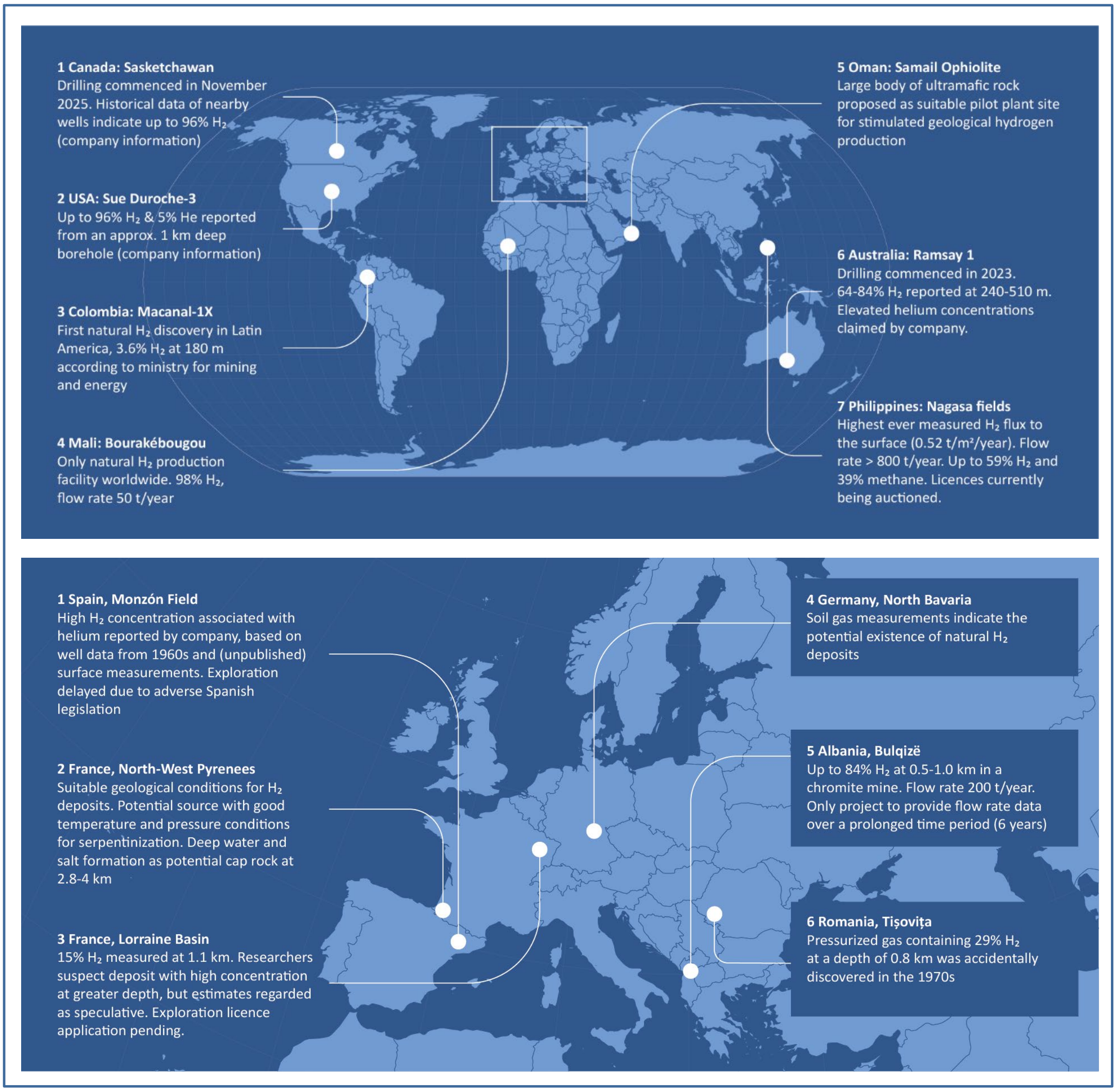

Figure 1: In the last few years, natural hydrogen research and exploration have increased in many regions. The map shows examples of projects and activities worldwide (above) and in Europe (below). Own Illustration. Data sources: Canada [17; 18; 19], USA [15; 16; 22), Colombia [23; 24], Mali [12; 13; 36], Oman [68], Australia [14; 25], Philippines [26; 53], Spain [27; 28; 29; 30], France – North-West Pyrenees [111], France – Lorraine Basin [1; 31; 32;], Germany [33], Romania [34], Albania [1; 107]

Infobox: Bourakébougou – the first hydrogen deposit used for energy supply

The first and so far only hydrogen deposit that has ever been put to human use is situated near the village Bourakébougou in Mali. The deposit was discovered by chance in 1987 during groundwater drilling. [1] The borehole was reopened in 2011 as part of a pilot project, whereby the hydrogen was used for the following five years to fuel an engine tuned to hydrogen. At a capacity of 30 kilowatts, it provided the village with electricity. [12; 35] Another 24 wells were completed in 2017 to 2018. [11]

With a reported flow rate of 1,500 m^3 per day (50 t/year) [13], the production is tiny compared to typical natural gas production. In most economic settings, fields with such a low flow rate could not reach economic viability. By comparison: high-quality production wells from conventional gas reservoirs in the North Sea produce more than two million m^3 per day [4] – over a thousand times more than the Bourakébougou Field.

Compared to other known natural hydrogen occurrences, the Bourakébougou Field is very shallow; some wells terminate as little as 100 metres below the surface. [4] The hydrogen concentration of the original well is very high, up to 97.4, but wells drilled subsequently showed lower hydrogen concentrations. [36] The remainder of the gas is mostly nitrogen with small amounts of helium, carbon dioxide and methane. [4]

The Bourakébougou Field proves that shallow deposits with high hydrogen concentrations can occur, sparking scientific and commercial interest in natural hydrogen. It must, however, be emphasized that such elevated hydrogen concentrations are likely to be exceptional. [7] The total volume of hydrogen present in the reservoir remains a matter of debate [37] and the origin and recharge mechanism of the hydrogen accumulation are still not fully understood.

Due to ongoing armed conflicts, research and exploration in the region have been impeded in the recent years.

2.4 Exploration methods: Research and development needs

There was broad consensus among our interview partners[3] that discovery of a major, commercially exploitable natural hydrogen deposit would represent the most important milestone. Such a finding would demonstrate that economically attractive deposits do exist and therefore likely would stimulate interest from industry and governments, thereby incentivising further investments in exploration.

Compared to oil and gas exploration, the **understanding of natural hydrogen systems is still in its infancy**. After more than a century of research and technological development aimed at understanding and characterizing petroleum systems, the global average commercial success rate of petroleum exploration is now at about 30 to 40 per cent. [4; 38] The success rate of natural hydrogen exploration at the current state of knowledge can be expected to be significantly lower. This may improve in the coming years with increasing understanding of hydrogen systems, especially if new exploration frameworks currently being developed prove successful. The discovery of the first confirmed commercial deposits would enable brownfield exploration, i.e., exploration in the vicinity of known accumulations. This would further enhance exploration prospects, since success rates for brownfield exploration, where the geological system is already established, are typically higher than for greenfield exploration in unexplored areas.

The exploration process consists of several steps and techniques, as shown in Figure 2. Most of the models and technologies needed are well established in oil and gas exploration. However, they need to be adapted to account for the properties of hydrogen and the geological settings in which hydrogen is generated and may accumulate. This requires an approach which integrates knowledge from other fields such as minerals mining, geothermal energy and microbiology. Natural hydrogen reservoirs may occur both in sedimentary

3 This chapter is based on the expert interviews. If no reference is given, statements are based on assessments of the interview partners.

and crystalline rock, but the source rock is most likely crystalline; thus, crystalline rock plays a more important role in hydrogen systems than in hydrocarbon systems. Most techniques from oil and gas recovery are tailored to sedimentary rock. Knowledge gaps regarding exploration in crystalline rock may be filled with knowledge from the fields of minerals mining and deep geothermal energy exploration. Minerals exploration may provide useful insights especially regarding potential source rocks, since minerals are found in the same type of rock, which is likely to generate hydrogen, e.g., Precambrian rock. Research and exploration of deep geothermal energy sources may, for example, contribute knowledge regarding the migration of hydrogen dissolved in saline waters. Another discipline required to develop a better understanding of natural hydrogen systems is underground microbiology, since hydrogen consumption by microbes may have a significant influence on the size of deposits.

Table 1 gives an overview of exploration methods, the current state of knowledge, and the development needed for natural hydrogen exploration.

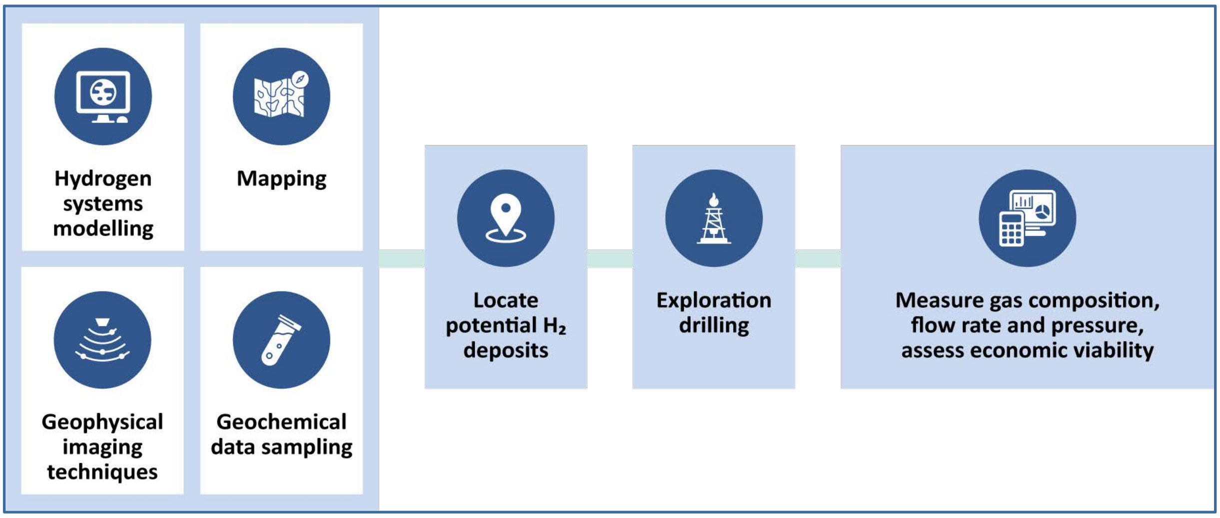

Figure 2: Exploration process. The more accurately potential deposits can be located in advance, the higher the chance of actually finding natural hydrogen during exploration drilling. Some parameters crucial for assessing economic viability can only be determined via drilling. Source: own illustration.

Methodology	State of knowledge	Development needed
Base for prospecting and exploration methods	Methods from oil & gas	Integrate knowledge from minerals mining, deep geothermal energy, underground microbiology
Hydrogen systems modelling	Concepts developed for oil & gas; hydrogen generation mechanisms understood in principle	Improve understanding of geological history; quantitative modelling of hydrogen generation, transport pathways (including aquifers), accumulation and microbial consumption
Mapping of hydrogen potentials	Mostly empirical data (often based on gas samples from oil and gas exploration or mining)	Predictive (based on understanding of hydrogen systems)
Geophysical imaging techniques	Optimized for oil & gas exploration in sedimentary rock	Adjust to hydrogen in crystalline rock, improve interpretation of data
Geochemical data sampling	Measuring technologies well established	Improve interpretation of data

Table 1: R&D needs. Research and exploration methods applied for oil and gas must be adapted and combined with knowledge from other fields to work for natural hydrogen. Source: own illustration.

Hydrogen systems modelling aims to reconstruct the different geological elements and processes involved in hydrogen generation, migration, accumulation and consumption. It can help to identify favourable geological settings (so-called play elements) with exploration potential. This may involve modelling of the present-day hydrogen systems as well as the reconstruction of the geological history. The latter may be especially relevant for hydrogen deposits which have developed over geological time scales. In addition, it may also contribute to our understanding of the present-day geology and help locate suitable source rocks and reservoirs. Regarding hydrogen generation, the fundamental mechanisms at a reaction level are known, but the quantitative modelling remains highly challenging. Reaction rates depend on many parameters including temperature, water availability, reactive surfaces, mineral composition and fracture connectivity. These parameters evolve dynamically through time as the hydrogen generation reaction progresses and alters the rock. There are still huge gaps of knowledge regarding the various subsurface transport mechanisms and the accumulation of hydrogen. One important aspect is that in some cases hydrogen is probably transported deep subsurface with water, either dissolved in water or by advection. To understand how hydrogen moves away from its source rocks, aquifers must be modelled as a potential transport network.

Mapping natural hydrogen potential provides a first-order overview of regions that may be prospective and can subsequently be studied in greater detail, for example through field studies comprising geophysical and geochemical methods. To date, most mapping efforts have so far been largely empirical, relying on the compilation of reported hydrogen occurrences. Much of this data stems from gas samples taken during gas and oil exploration or mining activities. A limitation of this empirical approach is that promising regions may be overlooked due to a lack of data and/or historical exploration interest. Since in most cases only the hydrogen concentration is reported, this does not provide much information about the potential for large deposits. Moreover, documentation of sampling and analytical procedures is often incomplete, making it difficult to evaluate whether measured hydrogen is of geological hydrogen or whether it stems from non-geological sources, such as microbial activity, the corrosion of drilling equipment, or frictional heating during drilling. Without understanding the geological context, measured concentrations do therefore not necessarily allow conclusions about potential hydrogen deposits. [1; 8]

Recently, there has been a shift from empirical to predictive mapping, including geological and geophysical data and modelling of hydrogen generation, transport pathways and accumulation. [4] A recent example of this is a natural hydrogen prospectivity map published by the U.S. Geological Survey, which identifies regions with potential hydrogen accumulations based on modelling hydrogen generation, migration, reservoir porosity, and seal capacity. [39] Similar mapping projects for other countries could facilitate research and exploration. To this end, the European Commission has published a call for tender in June 2025 which requests the mapping of natural hydrogen resources in the EU. [40] Initial academic research projects assessing the geological prospectivity in Europe on a continental scale are underway. [41; 42]

Geophysical imaging techniques such as seismic reflection and refraction, magnetometry and gravimetry data processing allow to infer the composition of the subsurface, e.g. type of rocks, from measurements of signals such as variations of the earth magnetic field, seismic velocity, or electrical conductivity taken at the surface. They are relatively cheap compared to drilling campaigns and therefore represent an economically favourable tool for early-stage regional prospect evaluation. Historically, these methods have been primarily developed for hydrocarbon exploration in sedimentary basins and for applications in the mining industry. Techniques and interpretation of the data need development to work well for hydrogen. Signals from geophysical techniques applied to crystalline rocks are generally more difficult to interpret since the rocks are typically heterogeneous in composition and strongly fractured, with highly variable physical properties over short distances. One major problem for the interpretation of geophysical data is that the responses of hydrogen-bearing rocks and other rocks may overlap. Integrating multiple geophysical methods can help reduce uncertainties and improve the robustness of subsurface interpretations. [8]

Geochemical data sampling comprises the analysis of both surface and subsurface samples. The analysis of surface samples such as soil gas and gas dissolved in shallow aquifers seeks to detect hydrogen leakage, and thereby reveal the location of underground reservoirs. It is commonly applied in the early exploration phase. Subsurface geochemical analysis can be conducted once a borehole has been drilled. Since exploration drillings aiming at natural hydrogen are just beginning, very little data from subsurface sampling has been published from these activities. Published records of subsurface samples containing hydrogen have so far been mostly limited to historical data from oil and gas exploration and global datasets developed over the past 30 years for investigations of subsurface microbiology. [5]

Several of our interview partners urged caution regarding the interpretation of measured hydrogen concentrations. Special care must be taken to avoid false positives [8]: Hydrogen generated by corrosion of metal drilling equipment, hydrogen created by thermal degradation of organic matter due to friction during drilling or hammering [43] and hydrogen produced by microbes might be mistaken for geologically generated hydrogen. Both artificial and microbial hydrogen can be a major factor in soil gas measurements. Protocols and best practice recommendations for interpreting measured data and avoiding false positives are under development. [4] Suggestions include using isotope chemistry to distinguish biological from geological hydrogen, and conducting measurements in winter when microbial activity is lower. Estimating the maximum expected hydrogen generation by non-geogenic processes may also be part of the analysis.

Drilling is generally the most technically demanding and costly part of the exploration process, yet it remains the only way to ultimately confirm the presence of a subsurface hydrogen accumulation. Once a deposit has been discovered, pressure, flow rates and gas composition can be measured and the economic viability assessed. Our interview partners expect that, although some modifications are required, proven drilling technology from natural gas exploration can be readily applied to hydrogen – at least when exploring in sedimentary settings. In crystalline settings, the engineering might be more challenging.

The more precisely prospective areas can be identified in advance, the higher the success rate of exploration drilling and therefore the lower the financial risk. It is therefore essential to narrow down the search with the previously described non-invasive and low-cost techniques, such as geophysical imaging and geochemical sampling, before drilling. Opinions among our interview partners differed regarding the appropriate timing for exploration drilling. Some pointed out that drilling is the only way to verify the results of geophysical imaging and modelling and that important data such as pressure, flow rate and gas composition can only be obtained by drilling. They also emphasised the opportunities of a successful find as a booster for the whole field of natural hydrogen research and development. Others voiced concern that too many unsuccessful exploration drillings might deter investors and funders and could lead media and the public to view natural hydrogen as a burst bubble. They advocated for a more careful and staged approach with the initial focus on developing a better understanding of natural hydrogen systems by non-invasive methods. Above all, the conditions under which hydrogen would accumulate need to be understood better to conduct more targeted exploration. [1]

One knowledge gap pointed out by many interview partners is the lack of **data on flow rates from known accumulations**. Data on flow rates from wells are only available for the Bourakébougou field in Mali. Since flow rates can only be measured once a borehole has been drilled and the drilling would in most cases be conducted by privately owned companies, measured flow rates are likely not to be published for confidentiality reasons. However, without such data, it is not possible to assess whether potentially economically viable hydrogen deposits exist.

Researching natural hydrogen systems may have **synergies with other research areas**. To highlight an example relevant for the decarbonisation of the energy system: Gaining a better understanding of the underground transport, accumulation, and consumption of natural hydrogen may also prove relevant for the underground storage of green hydrogen, thereby benefitting the development of a hydrogen economy as a whole.

3 Industrial-scale production of geological hydrogen

Since no economically extractable natural hydrogen deposit has been found so far[4], there is a high uncertainty regarding future cost and timeline for industrial-scale production. The following sections elaborate on the costs, technological challenges and time requirements for setting up industrial-scale production once an exploitable deposit has been found.

3.1 Production cost

Only a few estimates of the production cost of natural hydrogen have been published so far. A detailed description of the assessed studies can be found in the Appendix (Chapter A.4). The reported cost values depend strongly on the chosen method and the parameters of the test well and the parameters of the production scenario. Since the Bourakébougou field is the only one in production so far, there is very little real world data to base cost estimates on, which increases the uncertainty of such estimates.

The cost estimates from the studies range from a value as low as USD 0.14 per kilogram to a value as high as USD 6.82 per kilogram. Exploration companies commonly state that they aim for production costs of around or below USD 1.0 per kilogram for hydrogen from natural deposits [4] and below USD 1.5 per kilogram for stimulated hydrogen – as there is limited experience with this specific technology yet, these numbers have to be seen as cost estimates based on related technologies, not as real-world data (see Excursus: stimulated geological hydrogen production p. 27). Overall, it is expected that a cost level of low-carbon hydrogen of EUR 3 per kilogram (USDD 3.5 per kilogram) or lower is required in the long term, if it is to play a major role in the transition to climate neutrality in Germany. [44]

According to published studies, the parameters that affect costs strongly are the following: gas composition, flow rate, delivery pressure, hydrogen purity, the economy of scale and transportation costs. Additionally, geological conditions, infrastructure availability, distance to offtakers and regulatory frameworks can substantially affect overall project economics.

These levelised cost estimates indicate that natural hydrogen can potentially be cheaper than green hydrogen with costs between USD 3.9 and USD 13 per kilogram [45] and blue hydrogen (i.e., produced from natural gas via steam reforming with carbon capture and storage) with costs between USD 1.9 and USD 5.9 per kilogram. [45] It is expected that the cost of green hydrogen will decrease significantly in the coming decades, and countries with favourable conditions have set ambitious targets, such as Chile with USD 1.5 by 2030. [45] It has, however, been criticised that public studies often present cost projections for green hydrogen which might be overly optimistic. [46; 47]

The cost estimates for natural hydrogen also suggest that under favourable conditions, it could be in the cost range of grey hydrogen. The production costs of grey hydrogen are dependent on factors like natural gas prices, carbon prices and the size of production facilities and range between USD 1.0 and USD 4.3 per kilogram. [45] Since the production of grey hydrogen produces CO_2, it is not a long-term option if climate neutrality is to be achieved. However, its costs can be used as a benchmark in the near term.

Compared to other types of hydrogen, a greater share of the levelised cost of natural hydrogen will probably be capital expenditure. [4] For green hydrogen, electricity costs are the main driver, and for blue and grey hydrogen, natural gas costs are the main driver. [45] Conditions for financing investments, such

4 Experts suspect that the existing production facility in Mali is too small to be economically viable, at least in most economic settings.

as interest rates and the availability of venture capital, may therefore play a crucial role for natural hydrogen, while it will be less dependent on energy cost. A comparison of the levelised costs for different types of hydrogen can be seen in Figure 3.

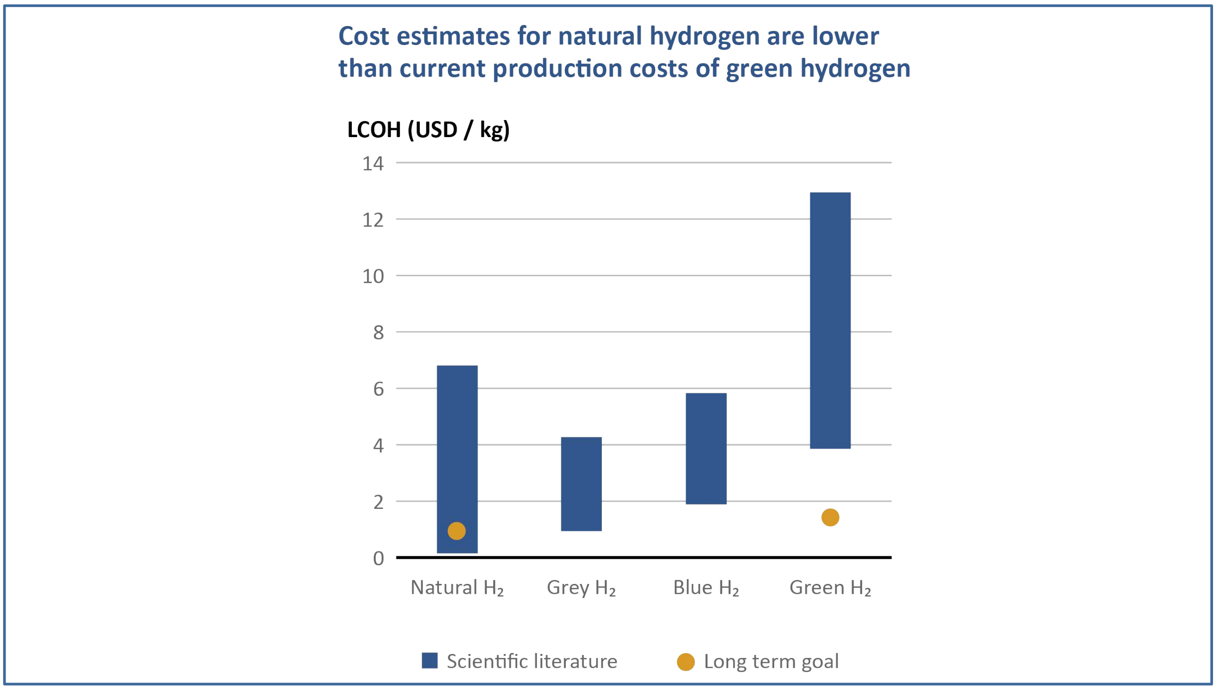

Figure 3: Levelised cost of hydrogen (LCOH) for different types of hydrogen. Own illustration with estimates from scientific literature based on [48; 49; 50; 51; 52; 4] for natural hydrogen and [45] for grey, blue and green hydrogen.

3.2 Key factors for economic viability

Whether exploiting a natural hydrogen deposit is economically worthwhile depends on the physical characteristics of the deposit as well as the economic environment, such as the specific use case for the hydrogen. The following factors are key determinants of economic viability (see also Figure 4):

- **Flow rate**: Due to economy of scale effects, a sufficiently high flow rate is essential for competitiveness. The Bourakébougou field in Mali is the only one where flow data from a well has been measured so far, amounting to 50 tonnes per year. Experts expect that flow rates several orders of magnitude higher are required for economic viability. Flow rates from seeps to the surface of up to 800 tonnes per year have been recorded for the Nagsasa seep in the Philippines. [53] While these cannot be equated to flow rates from wells and have limited significance for potential economic viability, they do indicate that substantial amounts of hydrogen are present underground in some places.

- **Total volume**: The overall quantity of hydrogen in the deposit determines for how long a given flow rate can be sustained. In natural gas exploration, an operational period of 15 to 30 years is usually expected for a production facility. [49]

- **Pressure**: Reservoir pressure has a direct impact on hydrogen production rates. Higher pressures enable more efficient and cost-effective extraction by lowering compression energy requirements and improving overall production efficiency. Maintaining well pressure is essential to ensure stable hydrogen flow rates and plays a key role in determining project economic viability. [48]

- **Hydrogen concentration**, the state of hydrogen and gas composition: The hydrogen concentration and the composition of the remainder gas have been identified as crucial for economic performance. [49] They determine the energy demand and cost of the gas separation required to purify the hydrogen. If the remainder gas contains methane or other hydrocarbons, this may lead to a higher carbon footprint overall (see Section 3.4). Undesired components such as H_2S may increase costs. If the hydrogen is not available as a free gas but dissolved in water, different separation processes are required. Most exploration companies appear to look for free gas deposits.

- **Rock type**: Hydrogen deposits may be present both in sedimentary and crystalline rock. However, exploration and exploitation are probably easier and cheaper in sedimentary rock, because technologies similar to those used in conventional oil and gas recovery can be used (see section 2.4).

- **Depth**: The depth of the deposit is an important parameter for the cost of the borehole – the deeper it is, the more technically demanding and expensive is the drilling. However, many of our interview partners expect large hydrogen deposits to be more likely and possibly limited to depths of several kilometres, where the hydrogen is not diminished by microbes. Since well pressure increases with depth, the given volume of a reservoir contains less hydrogen at shallower depths. [48] One of our interview partners suspected that there might be a sweet spot at medium depths of 1,000 to 1,500 metres, where the pressure of 100 to 150 bars is sufficiently high, but requirements for drilling technology are still manageable. Finding investors for drilling several kilometres is likely to be difficult, and start-ups seem to mostly focus on relatively shallow deposits.

- **Potential co-production**: Co-production of hydrogen with byproducts such as helium, lithium or geothermal energy may lead to the profitability of hydrogen deposits which would otherwise not be economically viable (see use cases in sections 4.1 and 4.3).

- **Proximity to offtakers**: Since the transport of hydrogen is technically challenging and expensive, economic viability is more likely if consumers are close to the deposit. Natural hydrogen may be especially attractive as an energy source in remote, off-grid locations where alternative energy supply is costly. Under such conditions, even smaller deposits might be economically viable. One such decentralised niche application may be mining operations (see Section 4.2). [4]

- **Willingness to pay for low-carbon hydrogen**: May be relatively high in Europe due to climate legislation. However, it depends on the price and quantities at which alternative low-carbon hydrogen (green, blue) or other decarbonisation options (such as electrification) are provided.

- **Regulatory context** such as tax regime for mining, mining laws, support schemes (see Chapter 5)

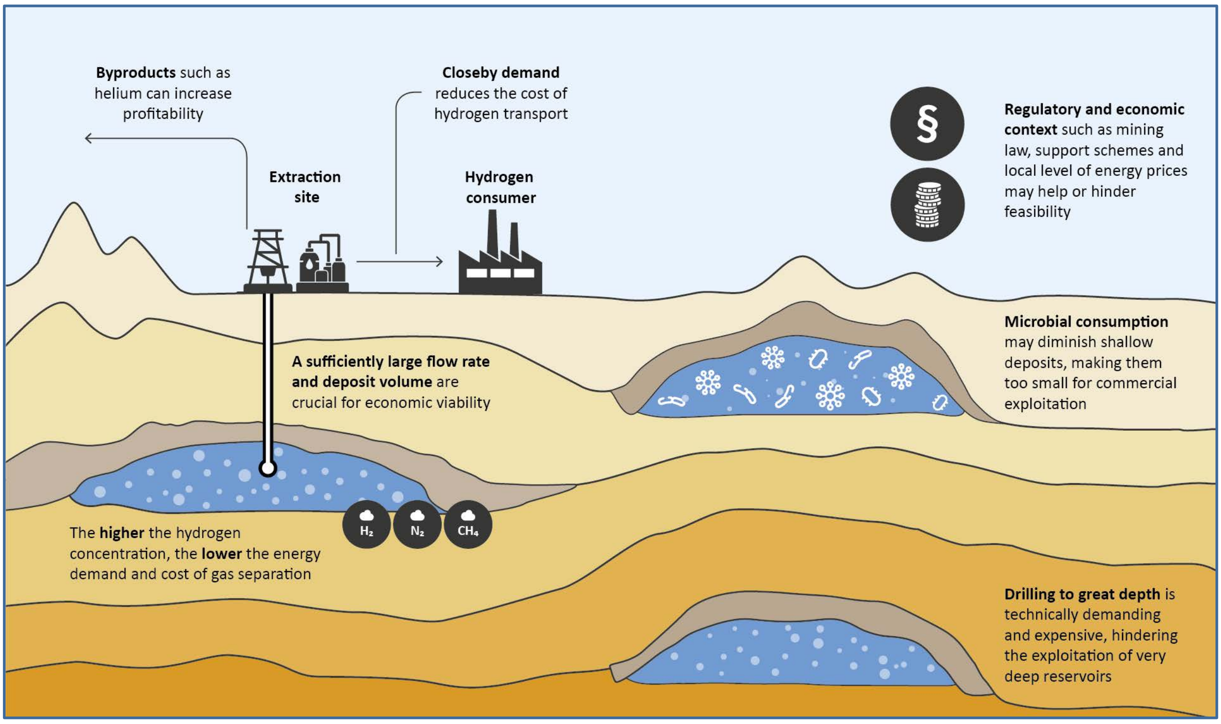

Figure 4: Key factors for the economic viability of natural hydrogen production. Source: own illustration.

3.3 Challenges for industrial-scale production

Given that a small production plant at Bourakébougou, Mali has been operated for some years and several exploration boreholes have been drilled, Musa et al. estimated a technology readiness level (TRL) [5] of six for natural hydrogen production, once a deposit has been found. [49] In that given case, a TRL of 6 would mean that a prototype was demonstrated in a relevant environment. If technologies from underground hydrogen storage, which already have a high degree of standardisation, can be applied, the TRL may be even higher. The TRL for the exploration is assessed to be much lower, at around two, by our workshop participants, meaning that so far only the technological concept has been formulated with no proof-of -concept.

Both in exploration and production, established methods from natural gas, mining, and geothermal technologies can be employed, combined and adjusted to hydrogen. Our interview partners agreed that the challenges lie in exploration. Once a sizeable deposit has been discovered, **setting up a production facility** is expected to be relatively straightforward. However, challenges may be project dependent. For example, extracting hydrogen from an aquifer may be more challenging than exploiting a pressurised free gas reservoir at a moderate depth.

Challenges for **drilling** depend on depths and lithology. Most natural gas fields are at 1,000 to 3,000 metres, therefore there is a lot of experience with technologies suited for this range. Drilling deeper is technically demanding and expensive. However, very shallow deposits may also require adjustment of the extraction technologies, e.g. due to low pressure of the gas. The type of rock is also an important factor. Since oil and gas are usually explored for and exploited in sedimentary basins, exploiting hydrogen deposits in such geo-

5 The TRL measures the level of maturity of a new technology's development on a scale of 1 to 9, where 9 means the technology has been proven to work reliably in a real world operational environment.

logical settings would be easier than in crystalline rock, since proven techniques from hydrocarbon production can be readily applied. In the case of crystalline rock, technological requirements are more similar to Enhanced Geothermal Systems (EGS) and technologies from this field may be adopted.

Exploiting natural hydrogen deposits does not require hydraulic fracturing ("fracking"). [4] There is, however, research on so-called stimulated geological hydrogen production (see Excursus p. 27), which does not utilise existing natural hydrogen deposits but introduces water to stimulate a reaction with suitable rocks to produce hydrogen. This requires the injection of fracturing fluids to enhance hydrogen generation and flow. [4]

Due to the **effects of hydrogen on steel**, high-alloy steel is needed for drilling and processing equipment. Other metals, elastomers and cement might be affected by hydrogen as well, which is a field of ongoing research. [4; 54] The presence of hydrogen may also increase biofouling and require measures like antimicrobial treatment. [4] With hydrogen expected to become a commonly used fuel and feedstock for the chemical industry, hydrogen-resistant materials must be developed in any case. Research and development in this field will therefore contribute to the implementation of a hydrogen economy overall.

Separating hydrogen from most other gases likely to be present in the gas mix of the deposit is proven technology. The exception is separating hydrogen and helium, where separation technologies are still under development (see Section 4.1). There is also ongoing development on in-situ separation (in the borehole). Possibly, hydrogen will be found dissolved in aquifers rather than as a free gas. Membrane technology to separate the hydrogen from the water at reservoir depths is being developed. [55]

3.4 Environmental impact and risks

An important factor for the environmental performance of natural hydrogen is its **greenhouse gas balance.** Hydrogen is not a greenhouse gas itself, but does contribute to global warming by extending the lifetime of methane in the atmosphere and by increasing ground-level ozone and stratospheric water vapour. With a global warming potential over a hundred years (GWP100) in the range of 4.3 to 12 [4], this indirect climate impact of hydrogen can be significant.[6] By comparison, the GWP100 of methane is around 30. [56] Like methane, hydrogen in the atmosphere is much shorter-lived than CO_2, and its warming effect is worst in the short term. Hydrogen's maximum GWP of 25 to 60 occurs around seven years after it enters the atmosphere. [57] The short-term climate impact is not well captured in the GWP100 and is commonly expressed by the GWP20, which measures the global warming potential over 20 years. It is about three times the GWP100 for both hydrogen and methane. [57] Thus, while the central estimate of the GWP100 for hydrogen is 11, the central estimate for the GWP20 is 33. [57]

To assess the greenhouse gas balance of natural hydrogen correctly, hydrogen leakages from production facilities, transport and utilisation appliances need to be assessed and accounted for. This is true for all types of hydrogen, as it has been shown that climate benefits from green and blue hydrogen can be severely diminished by hydrogen and methane leakages, especially in the shorter term. [54] It is expected that a major part of leaked hydrogen would be taken up by soils, reducing its climate impact. [4] It must be accounted for that the exploitation of natural hydrogen may reduce the amount of hydrogen leaking to the atmosphere via natural seeps and thereby actually reduce the climate impact.

Besides hydrogen leakages, energy consumption for the extraction and purification of hydrogen may contribute to the climate impact of natural hydrogen production, depending on the source of energy. Quite

6 The GWP is used to compare the impact of other greenhouse gases with CO2. The GWP of CO2 1.0 per definition. Thus, a GWP100 of 12 means that one tonne of hydrogen has the same climate impact as 12 tonnes of CO2 over a time span of 100 years.

frequently, natural hydrogen has been found mixed with methane. In this case the greenhouse gas balance depends on what happens with the methane. If it is combusted, it can provide energy for the hydrogen production, but causes CO_2 emissions. To prevent these emissions, the methane must be separated from the hydrogen and re-injected into the ground or directly separated in-situ and not be extracted with the hydrogen.

Initial life-cycle assessments of natural hydrogen production show that the characteristics of the deposit such as gas composition, will have a major impact on the greenhouse gas balance. [58] Given that no empirical data on hydrogen leakage, energy consumption, or waste streams of natural hydrogen production are available, the uncertainty is still very high. A working group of the Royal Society expects the carbon footprint of natural hydrogen to be lower than that of hydrocarbons. They consider it likely that the overall CO_2 emissions of natural hydrogen production from a deposit with high hydrogen concentration will be similar or lower than those of green hydrogen on a life-cycle basis. [4] However, this is merely an educated first guess which requires hardening up by further research.

Local environmental impacts at the extraction site are expected to be similar to those of natural gas production. They include the disturbance of local ecosystems, water use and potential pollution of water bodies. Induced seismicity is not expected to result from drilling for natural hydrogen, but may be an issue for the production of stimulated hydrogen (see Excursus p. 27).

Since hydrogen is an important food source for microbes, its extraction may **impact underground ecosystems**. Microbial underground ecosystems are poorly understood. If exploitable natural hydrogen deposits are discovered and large-scale production becomes an option, the effects on underground ecosystems need to be investigated.

3.5 The path to industrial-scale production: Timeline and milestones

In the last few years, considerable activity has expanded globally in the field of natural hydrogen. Worldwide, there are more than 110 companies involved in natural hydrogen, [55] most of them start-ups founded in the last ten years. Some of these start-ups managed to gain fundings from major players: The start-up Koloma received funding of USD 91 million, to a large sum from Bill Gates' Breakthrough Energy Ventures. [59] Fortescue invested AUD 21.9 million (~USD 15.3 million) in HyTerra for the Nemaha Project in Kansas, USA. [60] The start-up Snowfox Discovery received USD 30 million from a round led by bp Ventures. [61] Large private oil and gas companies therefore are following what is happening in the field of natural hydrogen: This corresponds to a typical dynamic observed in mining, where small exploration companies (juniors) lead the way into new exploration methods, and larger companies buy in later. [62] State-owned oil and gas companies such as Petrobras in Brazil and Saudi Aramco in Saudi-Arabia have been more active than privately-owned large companies so far. Since 2024, an increasing interest in mining companies can be observed. [55] For example, in Canada the mining company MAX Power Mining Corp. established a well to drill for natural hydrogen to assess flow rates, hydrogen concentration and volume. [63] Mining companies can contribute valuable experience with exploration in crystalline rock, while oil and gas companies usually work in sedimentary rock.

Exploration licences have been granted in several countries and some of them already have ongoing exploration drillings: the USA [64], Canada [63], France [65], Australia [2], China [66] and Mali (see infobox p. 16). Several other countries, including Poland and Germany (refer to Chapter 5.2), have amended their legal frameworks to enable exploration for natural hydrogen, or are in the process of doing so. Some countries like France and the USA also provide funding for research and/or exploration of natural hydrogen.

Our interview partners agreed that by far the most important milestone on a path to industrial-scale production is the discovery of an economically viable deposit. Once this is achieved, big oil and gas companies would enter the business of exploration and production and bring the necessary capital.

The estimates of our interview partners regarding the time required from the discovery of an economically viable deposit to industrial-scale production varied widely, from one year to over ten years. Time requirements will be country-specific, since the duration of licensing and approval processes varies greatly between countries. Company representatives mentioned time spans for granting exploration licenses ranging from three weeks in the USA to several years in France.

If legislation enabling the extraction of natural hydrogen is not yet in place in the respective country, adjusting the legal framework, including regulations on mining codes, for example, could easily increase the required time by several years.

In the best case, initial production sites could be in operation in Europe, the USA, and Australia before 2030. This would, however, require the discovery of exploitable deposits within the next, say, two years.

Excursus: Stimulated geological hydrogen production

In the long term, a potential alternative to searching for natural hydrogen deposits may be to artificially stimulate the formation of hydrogen underground by injecting a fluid containing water or catalysts into certain iron-rich rock formations. The injection fluid is then recirculated and the generated hydrogen is extracted from it. Hydrogen produced this way is often referred to as orange hydrogen. [67] The basic concept is shown in Figure 5.

Stimulated hydrogen production offers the advantage of being possible in many locations worldwide, since it only requires a suitable iron-rich lithology to provide source rocks instead of a complex combination of source rock, reservoir rock and seal. The exploration risk would therefore be lower. Scale-up may also be easier, since the production is not constrained by the volume and flow rates of natural deposits.

Stimulated geological hydrogen production is at an earlier stage of development than natural hydrogen production. To date, research has largely been limited to laboratory experiments. [51] The technology readiness level (TRL) is estimated at four. [68] Some of our interview partners suspect that it may take several decades to develop.

A major challenge is to speed up the serpentinisation reaction sufficiently to be feasible for commercial production. Research on the Samail Ophiolite in Oman indicates that for economically viable hydrogen production, the rate of hydrogen generation must increase by a factor of 10,000 compared to the natural rate. [68] Various physical, chemical and biological stimulation methods are under investigation.

Stimulation may consist of several steps, the first of which is increasing the water-to-rock ratio by hydraulic or electrical fracturing of the rock. [68] Since suitable rocks are crystalline, the required technology is more comparable to hydraulic fracturing applied for hot dry rock geothermal energy than for natural gas. Induced seismicity is a risk that must be assessed. The fracturing can be followed by the injection of fluids which catalyse the reaction that produces hydrogen and minimise microbial consumption. [68]

One advantage of stimulated hydrogen over natural hydrogen might be that it could be recovered at shallower depths, where large accumulations of natural hydrogen are likely to be rare because of microbial activity. Templeton et al. conclude that production may be possible as shallow as one to two km below ground. [68] The optimal temperature for serpentinisation of 200-300°C is generally found at greater depths only. [68] At shallow depths and thereby lower temperatures, the reaction is naturally slower. Since the reaction is highly exothermic, it must be brought to the required reaction temperature once and is then self-sustaining or must even be cooled. The optimal temperature to start the reaction can be reached by introducing hot water. Excess reaction heat can be recovered and utilised.

Hydration reactions such as serpentinisation lead to a volume increase of the rock, potentially closing fluid pathways. The impact on mechanical properties of the rock is not yet well understood. [69] It has been shown that the porosity and permeability of the rock can decrease significantly, [69] which may hinder water and hydrogen transport and thereby lead to a decrease in productivity of the well. It is therefore likely that the process will require frequent re-stimulation. The volume increase also creates a risk of induced seismicity.

Several of our interview partners expect the environmental risks to be higher for stimulated hydrogen than for natural hydrogen production. Potential negative impacts include changes in underground microbial ecosystems by the stimulation fluids and groundwater contamination. [68] The need for hydraulic fracturing ("fracking") and the injection of chemicals may also negatively impact public acceptance, especially in Germany and other European countries.

Enhanced hydrogen production requires more complex technology than natural hydrogen production. The higher investment needed is expected to lead to a higher levelised cost of hydrogen. [51]

It has been proposed to combine stimulated hydrogen production with permanent carbon dioxide storage. Ultramafic rocks are prone to mineralise CO_2, turning it into chemically stable, solid carbonates, thereby providing a long-term storage option. Hydrogen may be produced under certain conditions in a concomitant serpentinisation reaction. Injecting CO_2-saturated water may stimulate both carbonisation and serpentinisation. [70; 71] However, the basic conditions (pH, redox conditions, temperature, salinity etc.) for both reactions are different, potentially providing the possibility to "stake" the reactions in depth.

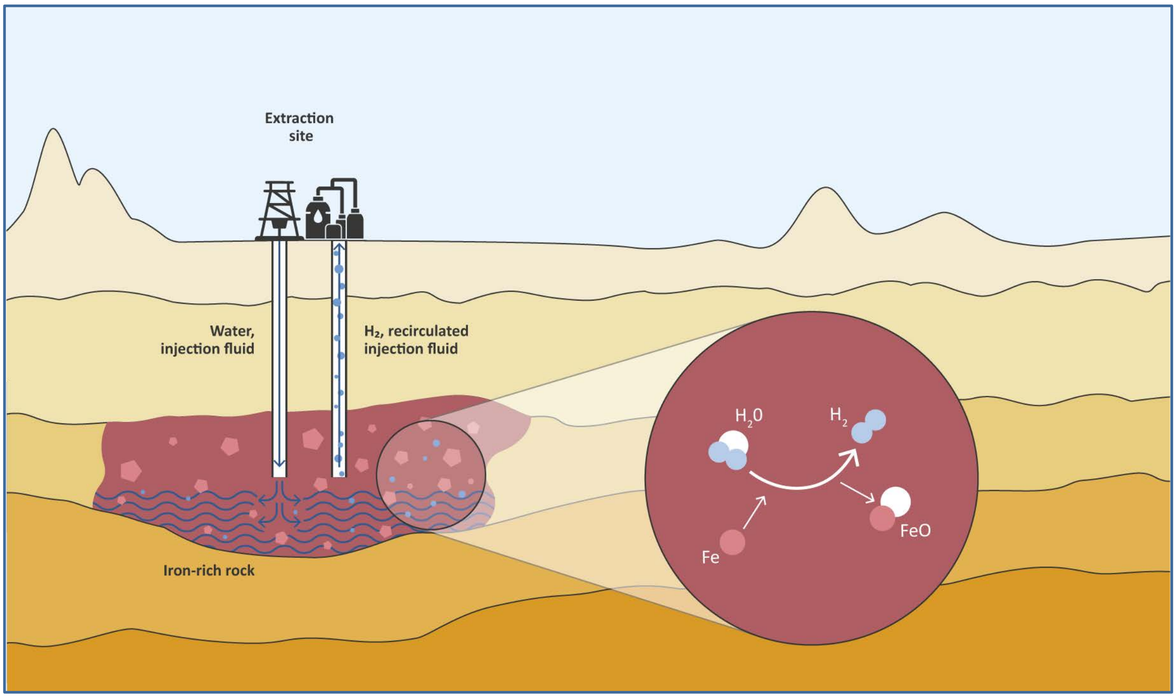

Figure 5: Stimulated geological hydrogen production. Source: own illustration.

4 Promising use-cases

As explained in section 3.2, the economic viability of the production of natural hydrogen depends on various factors. One factor that can improve the economic viability of natural hydrogen is the co-production of hydrogen with another valuable resource found in the same location. Co-production with tried and tested production of another resource is also a means of derisking natural hydrogen production.

Using natural hydrogen to provide energy for local operations may also improve its economic viability, since costly hydrogen transport can be avoided. Most interview partners agreed that decentralised use cases of natural hydrogen may be the most promising, at least in the short-term. Two reasons were given for this: 1) Some interview partners regard it as likely that most hydrogen deposits will be relatively small, therefore connection to a hydrogen pipeline would not be economically viable; 2) Building an extensive hydrogen transport infrastructure will take many years, therefore projects with local use of the hydrogen will be quicker to realise.

Three of the suggested concepts for hydrogen production and use are shown in Figure 6 and presented here in more detail.

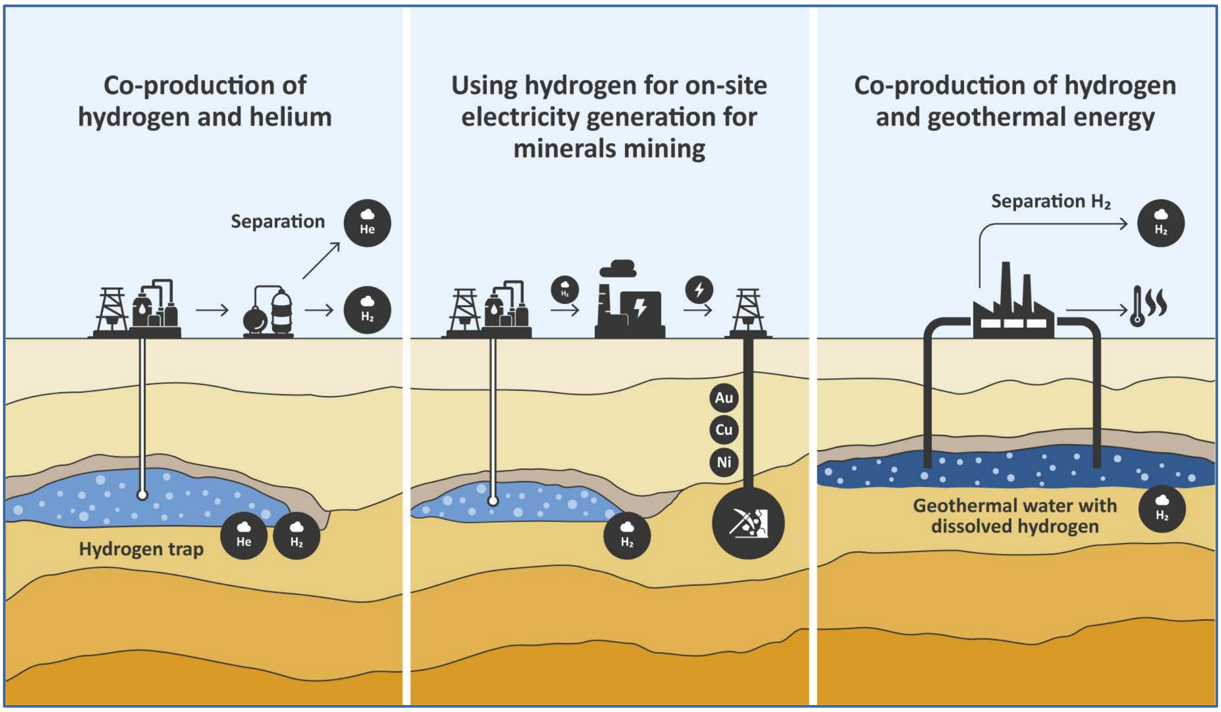

Figure 6: Possible co-production of natural hydrogen and other use cases: Co-production of hydrogen and helium, using hydrogen for on-site electricity generation for minerals mining, and co-production of hydrogen and geothermal energy. Source: own illustration.

4.1 Co-production with helium

Helium is an inert gas used, for example, in medicine, research, and manufacturing semiconductors. [72] According to the USGS, the worldwide production rate of helium was 180 million cubic metres in 2025 and 176 million cubic metres in 2023. [73] Helium is considered a non-renewable resource, and currently, the common commercially viable source of helium is co-production with natural gas. [72] Other production methods are extracting helium from the air or producing it from nitrogen fields. However, the purification of helium in any case is considered very energy-intensive and costly.

Helium is also commonly found in sites together with hydrogen, since both are reaction products of radiolysis. One example would be the Nemaha Project, Hy Terra in Kansas (with a confirmed presence of up to 92 per cent hydrogen and 3 per cent helium) and Gold Hydrogen at the Ramsay side in South Australia (86 per cent hydrogen along with 6.8 per cent helium). [both 72] Hydrogen and helium have also been found together at dozens of mining sites globally, often in a 1:1 ratio. [5]

As both helium and hydrogen are valuable resources, ideally both should be recovered when found together. However, separating the two gases remains a challenge. Possible separation technologies are cryogenic fractional distillation, membrane separation, and pressure and temperature swing adsorption. Cryogenic separation has been the only technique employed for large-scale helium extraction so far. [72]

Several companies are exploring for hydrogen as well as helium. According to the experts interviewed, they mostly tend to focus on helium, since it is more valuable, and regard hydrogen as a potential byproduct. One potential approach to avoid the need to separate of helium and hydrogen is to use the energy contained in the hydrogen onsite: the helium-hydrogen mixture is burned to generate the electricity used to power the gas extraction facility. The helium can then be easily separated from the combustion product, which is water. However, with improved separation technologies the production of natural hydrogen alongside helium could become more economically viable.

Another option for Germany specifically could be the co-production of lithium and natural hydrogen.

4.2 Decentralised energy generation for mining projects

Iron-rich rocks, where hydrogen is likely to be generated from, often also contain valuable minerals such as gold, copper or nickel. Mineral mining sites are big industrial complexes with a high energy demand. Since they are often in remote locations, sometimes far off the electricity grid, providing energy to the sites tends to be costly. Off-grid mining sites depend on onsite generation of electricity, often by diesel generators. [74] Extracting hydrogen at mining sites and using it to provide energy to the mining operations therefore seems to be an attractive use-case for natural hydrogen. [4] Since mining companies are likely to finance the natural hydrogen projects themselves, there is no need to attract investors in this use-case, which is likely to make the financing easier. [55] So far, however, only a few mining companies have started to explore natural hydrogen, e.g., Max Power Mining Corp. in Saskatchewan, Canada [63] and Bluejay Mining in the Outokumpu mining area in Finland. [75]

4.3 Co-production with geothermal energy

Locations suitable for geothermal energy production possibly also contain natural hydrogen, making them potential sites for hydrogen extraction. [4]

Research on this topic remains limited. One study in Iceland, where many wells for geothermal power production are located, suggested that co-production of geothermal energy and hydrogen could be a potential option. Currently the hydrogen released during geothermal operations in Iceland is simply emitted into the atmosphere and could be potentially recovered with gas separation. [76]

Other countries with potential for such co-production include, e.g., Turkey and Australia. [77]

In Germany, a pilot project launched by the company Tellus Energy Solutions in Northern Bavaria aims to establish local production of natural hydrogen in combination with shallow geothermal (40°) energy, aiming to provide a commercial proof of concept for this approach by 2030. Natural hydrogen could possibly also be associated with medium and high-temperature geothermal projects.

While most natural hydrogen exploration efforts seek to find free gas deposits, the Tellus Energy Solutions seeks to find hydrogen dissolved in water and therefore requires different separation technologies.

4.4 The potential role of natural hydrogen in the transition to climate neutrality

The extent to which geological hydrogen, as a low-carbon energy source and industrial feedstock, can contribute to the global transition to climate neutrality depends on two questions:

1. How much natural hydrogen exists in potentially usable, economically viable deposits?
2. How quickly can these deposits be extracted?

The estimates of our interview partners on the potential contribution vary widely. On the pessimistic side, some experts expect economically viable deposits to be insignificant compared to the amount of hydrogen needed in a future climate neutral energy system and industry. Others consider the potential contribution to be small in purely quantitative terms but still regard it as a relevant building block to diversify the hydrogen supply. Several interview partners expect natural hydrogen to play a role for decentralised use cases such as mining sites and other regional industrial hubs close to hydrogen deposits, but do not expect it to be a game-changer for the transition as a whole. On the optimistic side, some experts expect natural hydrogen to meet around ten to twenty per cent of the global hydrogen demand in the future. Preliminary results from one model for global natural hydrogen resource potential even suggest that natural and stimulated hydrogen combined could meet as much as half of the assumed annual hydrogen demand of several hundred million metric tons in 2100. [4; 10]

Regarding the timeline, natural hydrogen is unlikely to contribute to the climate targets for 2030, since this would require the discovery of several large deposits in the next two years or so. A contribution to the goal of climate neutrality by 2045 in Germany or 2050 in the EU in principle is possible but cannot be counted on. It is worthwhile to further research natural hydrogen as it would make the transition easier if it were discovered in significant quantities and to affordable prices, but at the same time, its potential prospects should not distract from building up green hydrogen production capacities.

From a global perspective, a decentralised energy supply with natural hydrogen, as demonstrated in Mali, may help to provide energy to people not connected to an electricity grid, thereby contributing to the sustainable development goal of affordable and clean energy for all.

Infobox: The role of low-carbon hydrogen in industry and energy system

For the transition toward a climate-neutral energy system and industry, large quantities of low-carbon molecular hydrogen (H_2) will be required. While hydrogen is currently used primarily as a feedstock in the chemical industry, it is expected to become an important energy carrier for applications where electrification is not feasible, particularly as a substitute for fossil fuels in industry and parts of the transport sector. For these applications, hydrogen can either be used directly, or it can first be converted into synthetic fuels by reaction with CO_2. Thus, global hydrogen demand is expected to rise steeply in the next two decades, from around 100 million tonnes per year today to 530 million tonnes per year until 2050 in a net zero emissions scenario. [6]

Currently hydrogen is predominantly produced from fossil fuels. In 2025, around 60 per cent of the global hydrogen production came from methane steam reforming (MSR) without carbon capture. [6] The remainder was mostly produced from coal gasification or as a by-product from naphtha crackers and steam crackers. [6]

To meet long-term climate targets, entire hydrogen demand must be met by low-carbon hydrogen. The prevailing strategy is to cover most future hydrogen demand with “green” hydrogen, produced via water electrolysis with electricity from renewable, non-fossil energy sources such as wind and solar power. In practice, however, green hydrogen production remains limited so far and market development was overestimated. In 2025, global production amounted to only about one million tonnes. [6] Moreover, recent assessments suggest that green hydrogen is more expensive than previously anticipated, and that market ramp-up is progressing more slowly than required to meet climate targets. [46]

Alternative production pathways with potentially low greenhouse gas (GHG) emissions include so-called “blue hydrogen” (produced MSR combined with carbon capture and storage – CCS) and “turquoise hydrogen” (hydrogen produced via methane pyrolysis). However, the actual climate impact of these pathways depends strongly on the rate of CO_2 capture and on upstream methane emissions, respectively. In addition, significant infrastructure challenges (CO_2-infrastructure) in the case of blue hydrogen and sufficient use cases for solid carbon in the case of turquoise hydrogen have to be considered. Their role in hydrogen production is so far negligible. In total, low-carbon hydrogen contributed only one per cent to global supply in 2024. [6]

Overall, low-carbon hydrogen is regarded as a key element of a climate neutral energy system and industry. So far the market development is not fast enough, which could slow down the transition to climate neutrality. [47]

5 Regulatory framework and societal decision-making

Developing natural hydrogen as a resource requires a legal framework. First and foremost, it must be defined under which conditions natural hydrogen can be explored for and extracted. A process of granting exploration and production rights must be set up. Given that the GHG emissions of natural hydrogen are expected to be similar to those of green hydrogen, it should be ensured that its decarbonisation potential is accounted for, e.g. by making it certifiable and eligible for the low-carbon fuel quota defined in decarbonisation legislation.

Hydrogen Europe, the association of the European hydrogen industry, states in its 2024 report that the regulatory framework for natural hydrogen is largely inadequate. [78] The following sections give an overview of current regulations with a focus on Germany and other EU countries as well as selected examples from non-EU countries.

5.1 Mining law

Until recently, natural hydrogen was not considered a geological resource and was therefore not covered by mining codes. This made the exploration and production of natural hydrogen difficult or impossible in many countries. Changes to regulations should enable production as well as exploration, since companies have no incentive to spend large sums on exploration if there is legal uncertainty regarding production in the case of successful exploration. In the last few years, several countries have changed their regulatory frameworks to acknowledge natural hydrogen as a geological resource and allow for its exploration and production. Other countries are in the process of doing so. In some countries, recognising hydrogen as a geological resource is accomplished by amendments to the mining laws; in other countries, it falls under oil and gas regulations. In countries where the extraction of hydrocarbons is banned for reasons of climate protection, it must be clarified how to deal with natural hydrogen deposits that contain methane.

In **Germany**, hydrogen (like helium) is not free to mine ("bergfrei"). This means that exploration is not prohibited, but the permission of landowners is required. Since natural hydrogen deposits may extend under the land of a large number of owners, seeking consent from all of them may increase the cost and effort for exploration companies substantially, and according to company representatives, would make natural hydrogen exploration unattractive. However, the draft of the Hydrogen Acceleration Act [79] states that hydrogen and helium shall be included in the list of "bergfreie" raw materials to facilitate the exploration and production of natural hydrogen.

France is the country in the EU which is most committed to driving the development of natural hydrogen. Natural hydrogen was first recognised as a resource in April 2022 and is covered by the French mining code. Exploration and research permits can be applied for by companies and are granted at a national level. [2]

Extraction of fossil resources is generally no longer permitted in France. The legislation for natural hydrogen extraction allows for the extraction of a limited amount of methane as a byproduct if it is used on site for meeting the energy demand of a natural hydrogen production plant. Any surplus of methane must be reinjected or converted into low-carbon hydrogen. The latter can be conducted via methane steam reforming with carbon capture and storage (blue hydrogen) or methane pyrolysis (turquoise hydrogen)

In **Spain**, an initial exploration license was granted in 2023. Under current legislation, however, production is not permitted because hydrogen falls under the regulation for hydrocarbons, which means its extraction is banned by the national climate law. [80]

In **Poland**, the Geological and Mining Law was amended in September 2023 to enable exploration and extraction of natural hydrogen production. [81] Hydrogen and noble gases are now subject to the legal provisions on hydrocarbons. [82]

In **South Australia**, hydrogen and by-products from hydrogen production were included in the Petroleum and Geothermal Energy Regulations in 2021. Companies intending to explore for natural hydrogen must apply for a Petroleum Exploration Licence. [83]

In the **USA**, exploration and extraction of natural hydrogen is possible under the existing legal framework for natural resources. Changes to the laws are therefore not required. [81]

5.2 Regulatory assessment of climate impact and emissions reduction

To assess the economic viability of a natural hydrogen project it is important to know how the hydrogen produced is classified under climate protection regulation and in certification schemes, for example, whether it can be counted towards renewable energy quotas in various applications. The relevant legislation is enacted on the EU level for the most part. So far, natural hydrogen is not explicitly mentioned in the relevant EU regulations, which leads to uncertainty regarding its status.

EU legislation distinguishes renewable hydrogen and low-carbon hydrogen. Renewable hydrogen is defined as hydrogen produced via electrolysis with electricity from renewable energy. Low-carbon hydrogen is defined as hydrogen which energy content is derived from non-renewable sources. It can be produced from natural gas with CCS, methane pyrolysis or electrolysis with electricity from the grid. Both renewable and low-carbon hydrogen must save at least 70 per cent of GHG compared to a defined fossil fuel alternative based on the full life cycle, including indirect emissions and upstream methane emissions. [84; 85] Definitions for renewable and low-carbon hydrogen are given in the *Renewable Energy Directive (RED III)* and the *Directive (EU) 2024/1788* which is part of the *EU Hydrogen and Decarbonised Gas Market Package*, respectively. The methodology to assess the GHG savings of low-carbon hydrogen is defined in the *Delegated Act on low-carbon fuels* (*Commission delegated regulation (EU) 2025/2359*).

Hydrogen certified as low carbon, as well as synthetic fuels derived from it, can be counted towards binding quotas for industry users and fuel suppliers in various sectors as defined by the *Renewable Energy Directive (RED III)* or the *ReFuelEU Aviation Regulation (Regulation (EU) 2023/2405)*. The RED III must be implemented in national law by the member states, and exact requirements may differ in detail.

The indirect greenhouse gas effect of hydrogen (see Section 3.4) is currently not included in life cycle emissions, since the uncertainty in determining it is considered too high. However, the *Delegated Act on low-carbon fuels* states that it should be included as soon as a scientific consensus emerges. This could be particularly relevant for the extraction of natural hydrogen, should it be included in the definition of low-carbon hydrogen at a later stage.

The *EU Taxonomy* is a market transparency instrument which defines environmentally sustainable activities aligned with climate neutrality by 2050. The criteria are detailed in the *Climate Delegated Act*. The manufacture of hydrogen is classified as sustainable if the GHG emissions over the life cycle are lower than three tonnes of CO_2 equivalents per tonne of hydrogen, which is equivalent to a 73.4 per cent reduction compared to the specified fossil fuel comparator. [86] The EU taxonomy regulation and Climate Delegated Act do not specify production methods for sustainable hydrogen. However, for natural hydrogen to be classed as sustainable, the methodology for the life cycle assessment, especially regarding the extraction process, would have to be specified to prove that the GHG emissions remain under the threshold.

The European Commission plans to develop the necessary legislation for sustainable natural hydrogen production. To this end, the Commission published a call for tender in June 2025 requesting an analysis of the current regulatory frameworks for natural hydrogen on the EU level and in the member states, including recommendations to develop coherent and supportive legislation. [87]

5.3 State funding

Given that geological hydrogen exploration is still in its infancy and that its benefits can be similar to those of green hydrogen, some sort of state support seems justified.

There is consensus among our interview partners that funding **research into natural hydrogen systems** is necessary. This includes projects aimed at understanding hydrogen generation, transport, accumulation and microbial consumption and developing methods to search for and recognise hydrogen deposits (see Section 2.4). For the latter, the correct interpretation of measured data is key. A working group of the IEA has identified scientific knowledge gaps in all these areas and recommends research priorities. [8] Funding guidelines and programmes should be adjusted to enable funding of geological hydrogen projects which can contribute to filling the identified knowledge gaps.

Research is already being funded at the EU level, albeit on a low level. Within the Horizon Europe framework, the programme "*Towards exploration and evaluation of European natural hydrogen potential*" seeks to develop methods to identify prospective areas in Europe, conduct life cycle assessments of natural hydrogen production, and estimate the levelised cost of hydrogen. The programme seeks to increase TRL from two to four, [88]thus targeting technologies which are at an early stage of development.

Some of the interviewed partners mentioned, that a couple of countries have their own dedicated research programmes for natural hydrogen: Australia is funding research directly through the federal states and the central government. France is providing research funding through the green hydrogen initiative. US funding is provided by the Advanced Research Projects Agency Energy (ARPA-E) as part of the U.S. Department of Energy.

To assess natural hydrogen potentials and encourage exploration, **national agencies** can support the nascent natural hydrogen industry by providing information such as **prospectivity maps.** The U.S. Geological Survey has made a substantive effort towards this goal by providing a *Geologic Hydrogen Prospectivity Map Explorer* with several map layers of geological and geophysical data for the U.S. territory. [39] The maps are based on knowledge about the geology of the U.S. as well as results from modelling of natural hydrogen systems, but to date do not include empirical data on measured hydrogen.

A similar approach for a prospectivity map for the EU has been initiated by the program "*Towards exploration and evaluation of European natural hydrogen potential*" – results cannot be expected before the end of 2026. The UK has also published a prospective map in a study. [89]

It is more controversial to what extent the state should **fund exploration**. Given that exploration – especially drilling – is expensive and the chances of finding hydrogen are actually relatively low, it can be debated whether the state should engage in such high-risk investments. On the other hand, drilling is the only way to confirm or refute the results of geological modelling and geophysical signal processing techniques, thus it is an indispensable step in gaining understanding of natural hydrogen systems and assessing natural hydrogen's potential as an economic resource. It is therefore desirable that data obtained, such as flow rates, are scientifically validated and published. Consortium projects between start-ups active in natural hydrogen exploration, oil and gas companies, mining companies and research institutions may combine the required knowledge and feedback data and insights into the academic research process. This could help the assessment of natural hydrogen potentials and thereby create a basis for informed policy decisions. Digitalisation may facilitate geoscience data management and the sharing of data, thereby speeding up the process of knowledge generation.

5.4 Public debate and community consultation

Although geological hydrogen has gained much attention in scientific publications in the last few years, there has been little coverage in the media. [81] It can therefore be assumed that knowledge about geological hydrogen in the general public is very limited.

The current research and exploration activities have little impact on society, but a broad societal debate will be required once exploitable deposits are found and plans are made to build extraction facilities. To our knowledge, the public acceptance of natural hydrogen has not been studied yet, but some learnings about which factors are key for public acceptance can probably be transferred from experiences with other types of hydrogen, renewable energy projects and other forms of resource extraction from the ground.

Surveys indicate that the attitude of the population towards hydrogen is generally positive and that the risks are regarded as manageable. Most respondents of such surveys consider hydrogen as trustworthy and promising, and express few concerns. [90; 91; 92] Whether this will also be the case for geological hydrogen must be investigated.

Part of the media coverage on natural hydrogen that does exist was criticised as sensationalist by several of our interview partners, since the articles rarely emphasise the high uncertainty regarding exploitable natural hydrogen deposits and may therefore create unrealistic expectations. For an informed societal decision, the potential role in the energy and industrial transition should be depicted realistically by scientists and media.

Regarding local acceptance for specific projects, perceived environmental and safety risks can play an important role. For technologies that require drilling the underground, such as deep geothermal energy, hydraulic fracturing ("fracking"), and carbon dioxide storage, induced seismicity and groundwater contamination are often among the main concerns. [93; 94; 95; 96] It is important to address these concerns and communicate clearly about scientific risk assessments and about which measures are being taken to minimise risks. It may also be important in communication to distinguish clearly between natural hydrogen extraction and stimulated hydrogen production, since the latter may involve greater environmental risks and requires hydraulic fracturing (see Excursus: stimulated geological hydrogen production p. 27). [68]

Another important factor for local as well as general public acceptance can be whether the actors involved are trusted. [97] Since natural hydrogen extraction will most likely be conducted by the oil and gas industry, low trust in this industry may adversely affect the attitude towards natural hydrogen. [81] On the other hand, local, decentralized use-cases, which are seen as the most likely first applications of natural hydrogen by our interview partners, may be favourable for local acceptance, especially if economic benefits remain in the community. [4]

Research on the acceptance of renewable energy projects shows that local opposition to projects tends to stem from multiple sources rather than a single one, with inadequate procedural equity[7] being a major driver of community resistance. [98; 99] Furthermore, projects involving new technologies (such as natural hydrogen) will need to address uncertainties and risk perceptions of local residents if they are to garner their approval. [97] Specificities of local contexts, lived experiences, regulatory frameworks, etc., should be carefully considered when designing and carrying out consultations. [97]

Deliberative and participatory approaches (rather than top-down approaches) aimed at informed consensus-building can positively affect public risk perceptions. Conversely, neglecting to address value debates and the broader societal and political concerns of local communities may result in negative risk perceptions, even when emphasising technical information to address these, thereby hardening opposition to projects. In the case of natural hydrogen, it may be important to communicate and discuss its potential role in the transition to a climate-neutral future, and to point out that it will not be a substitute but a supplement to renewable energies.

7 Procedural equity means that the decision making process is perceived as fair, transparent and inclusive.

6 Conclusion and policy options

Geological hydrogen has gained considerable attention in recent years from researchers, start-ups, oil majors and mining companies worldwide. This is linked to the prospect that geological hydrogen could be produced at significantly lower costs than green hydrogen and could therefore represent an attractive low-carbon energy resource. At the same time, the current state of knowledge is characterised by substantial uncertainties that limit its immediate relevance for energy system planning and climate policy.

This paper examined the potential of geological hydrogen and its potential contribution to the energy transition. It mostly focused on natural hydrogen while also explaining briefly the status quo of stimulated hydrogen. The information given is based on interviews and one workshop with experts from science and companies and supported with data from scientific literature. A list of the involved experts can be found in the Appendix.

The most fundamental uncertainty concerns whether economically exploitable natural hydrogen accumulations exist at all, and if so, at what scale. While the mechanisms of hydrogen generation in the geological subsurface are relatively well understood, and geological settings favourable to hydrogen generation are known to exist in many regions globally, the processes governing hydrogen migration, accumulation, and long-term preservation remain poorly understood. In particular, migration pathways through the subsurface and microbial consumption of hydrogen are not yet sufficiently characterised. As a result, it is currently unclear to what extent hydrogen generated in the subsurface actually accumulates in concentrations and volumes that are technically and economically extractable. This challenge is further intensified by the limited availability of scientifically validated data, as publicly communicated hydrogen volumes and concentrations are often based on company-reported information rather than peer-reviewed studies.

To date, no large-scale mineable deposit of natural hydrogen has been identified. Although many experts consider it likely that such deposits exist, their existence is by no means guaranteed. Most interview partners agreed that the discovery of a large, economically viable deposit would constitute the single most important milestone for the development of natural hydrogen. Such a discovery would likely trigger strong interest from major oil and gas companies, significantly increase private investment, and accelerate technological and regulatory development.

Should a mineable deposit of natural hydrogen be confirmed, production costs would depend heavily on site-specific characteristics, including flow rate, hydrogen concentration, reservoir depth and transportation costs from the source to offtakers or existing transport infrastructure. In favourable cases, experts expect that from a technological point of view, production could be started within a few years, as technologies from natural gas extraction could largely be adapted for hydrogen with manageable effort. However, this presupposes that permits are issued quickly and that skilled workforce for the various aspects of the operation is available in the region.

Stimulated hydrogen could have the advantage over natural hydrogen of being also applicable in lower surface areas and being easier to scale, since production is not limited by naturally occurring accumulations. However, the technology is still in its infancy as the research on it is mostly limited to laboratory experiments – the commercial deployment may take decades. A key challenge to this regard is accelerating the natural occurring process to reach economically viable production rates.

To diversify their value chains and de-risk hydrogen exploration, business models of start-ups often include by-products. Helium is especially attractive, since it is of high value and often co-exists with hydrogen. Another promising early use case is decentralised energy supply in remote locations, for example for mining operations. This is especially relevant because natural hydrogen is expected to occur in geological settings that are often also associated with valuable mineral resources. In addition, concepts for the combined exploitation of geothermal energy and hydrogen have been proposed, which could also help reduce exploration risks.

To make informed policy decisions on if and how to include natural hydrogen in plans for the transition to climate neutrality, it is important to understand its potential contribution and to reflect the still open questions and uncertainties. Most interview partners think it is likely that natural hydrogen could play a role in certain decentralised applications. Regional industrial hubs that supply natural hydrogen to nearby consumers are seen as the most likely contribution. Opinions are divided on the importance of natural hydrogen for achieving climate neutrality. Most experts do not believe that it will be a real game-changer, but rather one piece of the puzzle.

Beyond availability and cost, environmental performance is a crucial criterion for assessing the potential role of natural hydrogen in decarbonisation. Comprehensive environmental assessments, including LCAs, are required. The accurate accounting of GHG emissions is essential to determine whether natural hydrogen meets the emission-reduction thresholds defined in decarbonisation frameworks such as the EU Renewable Energy Directive or ReFuelEU Aviation. If these criteria are met, natural hydrogen should be made certifiable as a low-carbon fuel that can be counted toward regulatory quotas. Initial informed estimates suggest that life-cycle GHG emissions could be comparable to those of green hydrogen, but this strongly depends on site-specific factors. In particular, the handling of co-occurring methane is crucial, as methane leakage would significantly worsen the climate balance of natural hydrogen. Moreover, the understanding of indirect climate effects of hydrogen remains limited, although this issue applies to all hydrogen pathways, not only natural hydrogen. The indirect climate effects of natural hydrogen will be especially relevant if leakage rates from extraction facilities are high. Technical leakage also needs to be put into perspective to naturally occurring leakage to the atmosphere via seeps.

From a policy perspective, there are several measures that could promote a better assessment of natural hydrogen without prematurely committing to it as a pillar of the energy transition. First, legal frameworks should be adapted to explicitly allow the exploration and extraction of natural hydrogen, clarifying its status within mining and energy law. Second, public funding for research into geological hydrogen systems appears relatively uncontroversial and potentially beneficial. Given the central role that most of the existing transformation (scenario) studies attribute to low-carbon hydrogen in climate-neutral energy systems, an additional and potentially low-cost source of low-carbon hydrogen could definitely ease the path to climate neutrality. Moreover, knowledge gained from natural hydrogen research—such as the development of hydrogen-resistant materials or improved subsurface modelling—may also benefit other hydrogen technologies, particularly underground hydrogen storage.

Another low-regret policy option is to raise awareness of natural hydrogen as a potential resource within the oil and gas industry, as well as the mining sector. Hydrogen is not routinely measured in standard exploration and production workflows. Promoting the inclusion of hydrogen in mud gas analysis and other subsurface monitoring activities could significantly improve the data basis on natural hydrogen occurrences at relatively low cost.

Geological surveys can further support exploration by compiling, analysing, and providing existing geological and geophysical data in the form of prospectivity maps. Such publicly accessible information can reduce information gaps and help private actors identify promising areas for exploration.

More challenging is the question of whether and to what extent public funding should support drilling-based exploration. Drilling is expensive and associated with high project-specific risk, yet it remains the only method to ultimately confirm or refute indications from geological modelling, geophysical surveys, and geochemical measurements. One promising approach to de-risk exploration is to combine natural hydrogen exploration with the exploration of other subsurface resources, such as geothermal energy. Funding exploration projects with a strong scientific component could simultaneously advance knowledge of geological hydrogen systems and clarify the realistic potential of natural hydrogen as an energy resource.

Germany so far has not been considered to have huge deposits of natural hydrogen based on its geology, but some research projects and start-ups are looking into the option of combining its exploration with geothermal energy and helium extraction in decentralised use cases. The most important step in Germany would be to adapt the legislation to include helium and hydrogen as “bergfreie” (free to mine) raw materials as announced in the Hydrogen Acceleration Act. As a consequence, permission by the landowners under whose land the hydrogen deposit lies would no longer be required for exploration and extraction, which would substantially reduce cost and efforts for exploration companies. Furthermore, it could be advisable to fund research programmes to secure independent, scientifically-proven data to gain more insight into the potential of the resource.

Finally, given the current level of uncertainty, natural and stimulated hydrogen cannot be relied upon as a cornerstone of the transition to net-zero emissions. Other low carbon hydrogen options, particularly green hydrogen, as well as electrification must be scaled up regardless to meet climate targets. Only if large, economically exploitable deposits of natural hydrogen are discovered and their environmental performance proven should natural hydrogen be integrated as an additional building block in long-term transition strategies.

A Appendix

A.1 Natural hydrogen generation processes

An overview of subsurface hydrogen generation processes is given in Figure 7.

Hydration or oxidation reactions of certain types of iron-rich rock are considered by many experts to be one of the most relevant sources of potentially extractable natural hydrogen deposits. The reactions require the presence of water and can occur in various iron-rich lithologies, such as Fe-silicates, Fe-carbonates, and Fe-oxides. Among them, **serpentinisation**, is one of the most intensively studied processes in the scientific literature. It involves the hydration and oxidation of ultramafic rocks[8], namely peridotites composed mostly of olivine**,** and leads to the formation of serpentine minerals, magnetite, and molecular hydrogen. The world's largest exposures of ultramafic rock are in the Precambrian continents. [5] Another typical geological setting known for serpentinisation is found at plate boundaries, especially along mid-ocean ridges, where seawater reacts with mantle-derived peridotites. [1] However, experts regard such marine environments as unsuitable for the industrial production of natural hydrogen due to their remoteness and great water depths and the associated technical challenges**.** For commercial exploration, continental settings are regarded as more favourable. In compressional orogenic belts such as the Pyrenees and the Alps, mantle-derived rocks may occur in large tectonic wedges, providing potentially suitable protoliths for serpentinisation-driven hydrogen generation. The serpentinisation reaction is strongly temperature-dependent. In its optimal temperature range of 200 to 350°C it is a relatively fast reaction on geological timescales. [100] However, such temperatures are typically found at great depths of seven to ten kilometres under average continental geothermal gradients. [1] In contrast, many peridotite settings on continents, like ophiolites, have a maximum depth of three to five km. [8]

Another process regarded as promising in terms of industrial-scale natural hydrogen production is **radiolysis**. In this process water is split into hydrogen and oxidized species (O_2 or H_2O_2) by the ionizing radiation produced during radioactive decay of elements such as uranium, thorium, and potassium. Radiolysis therefore occurs primarily in rocks enriched in these radioactive elements, including rock salt and granite. [1] Since radiolysis depends on the decay rates of the radioactive elements, it is much slower than serpentinisation. Over geological timescales, however, significant quantities of hydrogen may accumulate if migration losses and consumption processes are limited. Besides hydrogen, radiogenic decay of uranium and thorium also produces helium (He). This makes the co-production of helium and hydrogen potentially interesting (see Section 4.1).

Hydrogen generation through thermal decomposition of kerogen and hydrocarbons is also the subject of ongoing research. [101; 102] Although laboratory experiments have demonstrated that hydrogen can be produced during high-temperature cracking of organic matter, its relevance for the formation of potentially commercial H_2 accumulations remains uncertain. [8] Hydrogen is generally consumed during the formation of hydrocarbons, which may limit the net amount of hydrogen available from organic-rich source rocks. [8]

Several **other abiotic hydrogen generation processes** exist but are generally regarded as having limited potential for industrial natural hydrogen production. It has been demonstrated in laboratory experiments that hydrogen is generated by mechanoradical[9] reactions during **mechanical fracturing of rocks.** [103] This

8 Ultramafic rocks are magmatic rocks with less than 45% silica content. The earth mantle is largely made of ultramafic rocks. Peridotites are a type of ultramafic rock and the most common rock in the upper mantle. It consists mostly of the minerals olivine (which is a magnesium iron silicate) and pyroxene.

9 Mechanoradicals are free radicals generated when chemical bonds in a solid are broken by mechanical forces such as shearing.

process potentially occurs along active faults, where rock deformation creates fresh mineral surfaces and reactive radicals. It is uncertain how much hydrogen is generated by this process in natural settings, and whether it contributes significantly to potentially exploitable accumulations. [8] Mantle degassing, **volcanic activity along deep fault systems,** hydrothermal sources, and degassing of SO_2 under low pressure can also generate hydrogen but are not considered relevant for potential commercial extraction. [1; 4, and references therein]

Some researchers have proposed that **fluids upwelling from the deep Earth mantle** may be a potentially large source of hydrogen. [10, references therein] This is, however, hypothetical and controversial. The underlying hypothesis of the "primordially hydridic earth" [104] which postulates large-scale hydrogen outgassing from the deep interior, is not supported by peer-reviewed scientific literature. While molecular hydrogen can occur in the deep mantle, thermodynamic equilibrium studies indicate that at pressure and temperature conditions corresponding to depths shallower than about 90 km, hydrogen exists mostly in the form of water. [8; 105; 106] This implies that free molecular hydrogen is unlikely to remain stable during ascent through the upper mantle and crust. Isotope chemistry analysis has been applied to noble gases associated with hydrogen found in several typical geological settings that are potentially suitable for commercial exploitation, and no evidence of mantle origin[10] has been found. [7; 4, and references therein] The working group of the UK Royal Society on natural hydrogen concluded that "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." [4, p. 7] Similarly, a scientific paper by members of an IEA working group concludes that "The potential for mantle-sourced H_2 in the Earth's crust cannot be completely discounted, but the available evidence indicates that it is quite unlikely that it could form appreciable accumulations." [8, p. 5]

Hydrogen can also be produced by several **microbial metabolism** processes including fermentation, nitrogen fixation and acetate oxidation. While natural microbial processes are not considered relevant for industrial-scale production, there is research on introducing microbes such as purple non-sulphur bacteria into underground environments to stimulate hydrogen generation. [1] For the assessment of natural hydrogen resources, microbial hydrogen is relevant because it can be mistaken for geologically generated hydrogen in soil gas measurements, thus leading to false conclusions about exploitable hydrogen deposits. [8]

10 "Mantle origin" refers to hydrogen rising up directly from the mantle. It is uncontroversial that hydrogen is generated by serpetinisation from rocks that were once in the mantle but are now in the crust, such as mantle wedges and kimberlites.

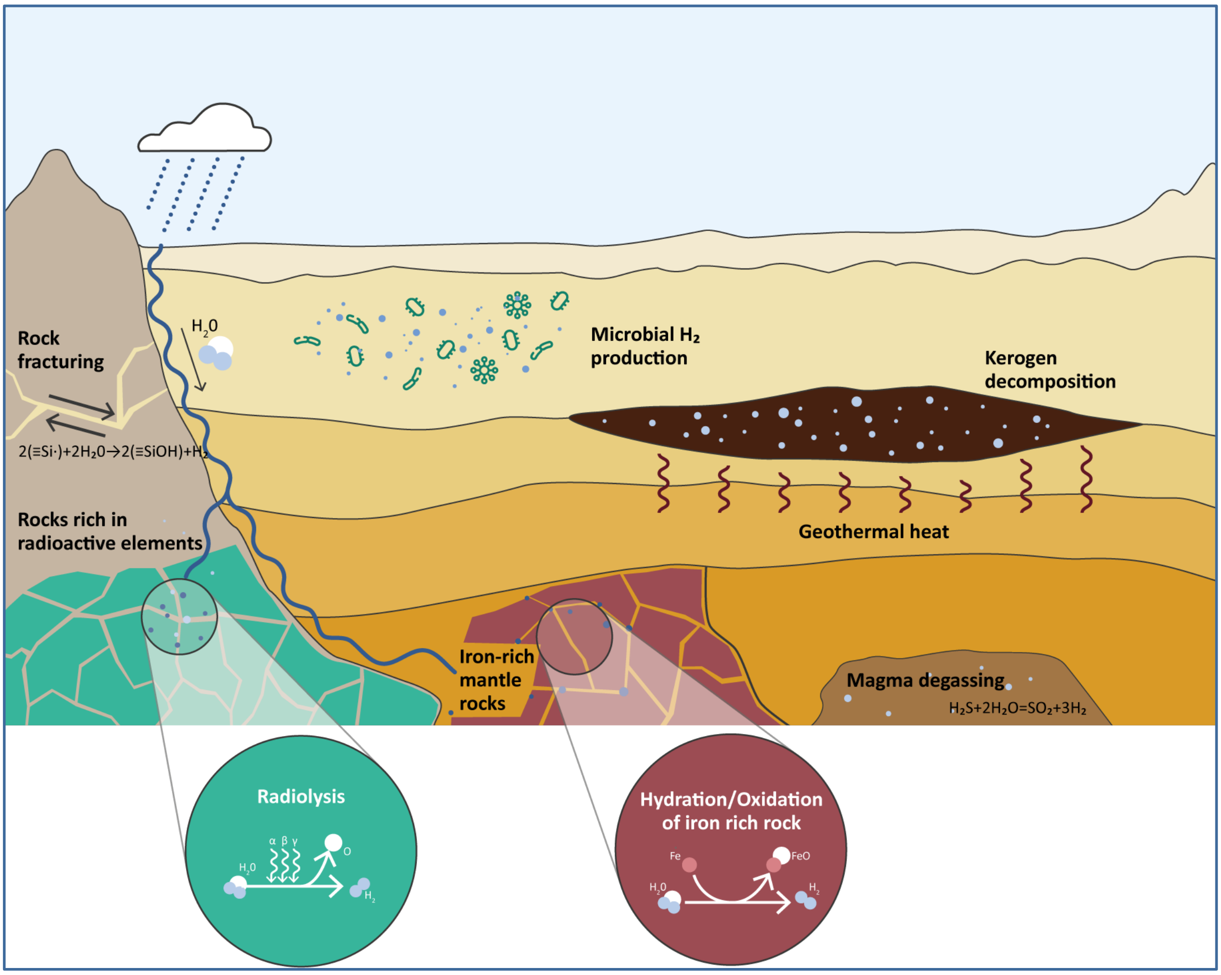

Figure 7: Subsurface hydrogen generation processes. A number of abiotic and microbial processes generate hydrogen, but only a few processes seem to offer potential for industrial-scale hydrogen extraction. Source: own illustration.

A.2 Underground migration, accumulation and durability

Besides the hydrogen generation, it is important to understand how and where hydrogen migrates from the source rock, whether it accumulates in economically recoverable volumes or diffuses towards the surface, and how quickly it is diminished by chemical reactions and/or microbial consumption. The uncertainties regarding these processes are even higher than for hydrogen generation. As a consequence, there is currently no scientific consensus regarding the expected prevalence, volume, or hydrogen concentrations of deposits or typical depth distribution of natural hydrogen accumulations.

Two fundamentally different types of hydrogen systems are currently discussed: **continuously refilling, short-term systems** and **long-term accumulation systems** in which hydrogen is trapped and preserved in a reservoir. [8] Hybrid forms between these two systems are also conceivable. Long-term accumulation systems are conceptually analogous to conventional hydrocarbon systems, meaning that established exploration and development models from the oil and gas industry can, in principle, be adapted.

Continuously refilling systems would require ongoing hydrogen generation at rates equal to or exceeding losses through seepage, diffusion, and biotic or abiotic consumption. Such systems could be considered renewable on a human timescale, if the generation rates are high enough to compensate significant human extraction rates (see Infobox p. 13). Given the slow rates of the relevant hydrogen generation processes such as serpentinisation and radiolysis in natural systems, these are considered an unlikely scenario. [8] Moreover, measured natural hydrogen flow rates and concentrations are typically far below levels considered necessary for commercial viability from techno-economic assessments. [9]

There has been some research work on analysing whether known hydrogen systems are likely to be continuously refilling or accumulated. [8, and references therein] For the Bulqizë chromite mine in Albania, where a flow rate of 200 t/year has been recorded over several years, mass-balance considerations indicate that present-day serpentinisation alone cannot sustain the observed flow rates. Based on gas proportion modelling (N_2–CH_4–He), the system may have been active for on the order of ~26,000 years. [107; 108] For the field in Bourakébougou, Mali (see Infobox p. 16), it was shown that pressure did not decline despite the extraction of hydrogen. While some researchers interpret this as evidence for rapid, continuous hydrogen generation, others regard this explanation as speculative, as generation rates sufficient to sustain industrial production are difficult to reconcile with known geological processes. Alternative interpretations propose that the shallow deposit is being recharged from deeper reservoirs, [4] or that hydrogen is mostly dissolved in formation water from where it is released into small gas pockets. [37] Importantly, recharge of a shallow reservoir from deeper sources does not necessarily imply a self-replenishing system driven by rapid, ongoing generation. Instead, it may reflect redistribution within a larger, previously accumulated hydrogen system.

In oil and gas exploration, the concept of a petroleum system is used to describe the essential geological elements and processes required for hydrocarbon accumulation. It comprises a source rock, migration pathways, a reservoir rock, and a seal. A geometric and stratigraphic configuration in which reservoir and seal combine to enable the accumulation of hydrocarbons is referred to as a trap. This model can also be applied to the analysis of hydrogen systems with long-term accumulations.

The **source rock** generates hydrogen; the relevant processes are discussed in the previous section.

Carriers are structures or fluids through which hydrogen can migrate away from the source rock, such as permeable sediments or rock fractures. Compared to hydrocarbons, hydrogen is a very small and reactive molecule. Once hydrogen has been generated, it is likely to migrate away from the source rock via diffusion, advection in a gas phase or dissolved in a fluid. [1; 8] Diffusion occurs along concentration gradients and is inherently multidirectional rather than strictly unidirectional. This leads to hydrogen being more dispersed and is expected to be much more relevant for hydrogen than for natural gas. In contrast, advection enables focused migration along permeable pathways such as fractures, faults, or porous strata. Natural hydrogen may be present as a free gas or dissolved in groundwater. Since the solubility of hydrogen in water increases with depth, it may migrate dissolved in water along aquifers and **exsolve** as pressure decreases at shallower levels, thus forming free gas deposits or escaping into the atmosphere.

Reservoir rocks are characterized by a sufficiently high porosity, providing pore space for gas storage, and adequate permeability, meaning that the pore spaces are interconnected and allow fluid flow. Typical reservoir rocks **include porous** sandstones as well as fractured lithologies, such as carbonates or crystalline basement rocks with well-developed fracture networks.

The **seal** is a cap rock with low permeability that creates a barrier above the reservoir, preventing the hydrogen from escaping. Potential cap rocks include clay [1] and rock salt. [109] Due to the small size of hydrogen molecules, diffusion processes are much more relevant than for natural gas and the permeability of the seal must be very low to keep the hydrogen in place over geological timescales. Typical cap rocks of petroleum systems, such as mud rocks and shales, may not work for hydrogen. [109] Firstly, their pore-sizes and apertures may be too large to contain hydrogen. Secondly, it has been shown that exposure to hydrogen can increase their porosity and permeability, thus impairing seal integrity. [109]

For hydrogen deposits to form and persist there must be a **trap**, a geological configuration in which a reservoir rock and an effective seal act together to prevent further migration. On a geological time-line, the trap must already have been in place when the hydrogen generation occurred, and it must have remained intact until the present day.

Some examples of geological settings which may host commercially promising natural hydrogen systems in Europe are presented in the following Infobox.

Infobox: Suitable geologies for finding natural hydrogen in Europe

As the preceding explanations on hydrogen systems show, several factors must coincide to facilitate natural hydrogen generation and accumulation, including a source rock, water supply (for serpentinisation and radiolysis), and migration pathways to a suitable reservoir overlain by an effective seal within a trapping structure. Hydrogen occurrences have been documented in a number of geological settings, including peridotites in ophiolite complexes, crystalline rocks of magmatic and metamorphic nature, and carbonates and sandstones in sedimentary basins. [8] This illustrates that suitable conditions for hydrogen generation and accumulation may exist in a variety of geological settings.

Several promising regions have been identified in Europe: A prospectivity mapping project (not peer-reviewed) taking into account geological indicators of hydrogen generation, reservoir quality and sealing capacity identifies high-prospectivity regions in Hungary, Denmark, Poland, Serbia and parts of France and North Macedonia. [41] The analysis also shows that some regions, despite having a high potential for hydrogen generation, show low prospectivity due to the absence of suitable reservoirs and seals. [41]

Hydrogen deposits potentially occur in compressional tectonic settings such as mountain ranges that formed after the closure of rift basins. In Europe, the Pyrenees, the Alps and some regions in the Balkans, namely parts of the Dinarides, may provide favourable conditions: These regions contain mantle rocks that were brought close to the Earth's surface by plate tectonic processes and can serve as a potential source rock for natural hydrogen generation through serpentinisation. Depending on burial depth and geothermal gradient, such rocks may reside within temperature ranges conducive to efficient serpentinisation. [100] The high topography of the mountain range can enable deep meteoric[11] water circulation. [110] which enhances interaction between water and potential source rocks for hydrogen generation. Subsequently, the generated hydrogen could migrate towards the adjacent mountain foreland basins, which can offer ample potential reservoir and seal rocks where the hydrogen could accumulate. [111]

Another geological setting that may be favourable for the accumulation of natural hydrogen is intracratonic sedimentary basins. In such systems, hydrogen can be generated through water–rock interactions, including the oxidation of Fe^{2+}-bearing minerals and radiolysis of water driven by the radioactive decay of uranium, thorium, and potassium in basement lithologies. The latter may also produce helium over geological timescales. The North German Basin and the broader Central European Basin System represent potential examples of this setting, where thick sedimentary successions overlie crystalline basement rocks and may provide suitable reservoir formations, such as Permian Rotliegend sandstones or Triassic sandstones, together with effective regional seals such as the Zechstein evaporites. Basement-rooted fault systems may act as migration pathways, allowing hydrogen and helium generated at depth to migrate into overlying sedimentary reservoirs, where the gases could accumulate in structural or stratigraphic traps. The region has been heavily investigated by the petroleum industry in the past and is currently being explored for helium, but so far, no occurrences of high concentrations of hydrogen have been reported.

The volume of hydrogen deposits depends critically on the efficiency of **preservation** of the hydrogen. Once generated, hydrogen may be lost through chemical reactions (e.g. methanogenesis), physical processes

11 Meteoric water is water from precipitation that infiltrates the ground.

(e.g. adsorption at coal or clay), as well as by biological consumption by microorganisms. Modelling results indicate that **biological consumption** has a large impact on hydrogen potential, [10]supported by numerous case studies in hydrogen-producing systems. [4] Microbial activity is highly sensitive to local conditions such as salinity and availability of nutrients and water availability and may therefore vary greatly. In places where meteoric water can circulate through permeable fracture networks, microbial activity is often elevated. [112] Case studies show that in some cases, up to 90 per cent of the produced hydrogen may be consumed biologically. [10, and references therein; 113] Several of our interview partners suspect that shallow hydrogen deposits will be relatively small in most cases due to high biological degradation. Large hydrogen deposits may be confined to greater depths of at least four to five kilometres, where temperatures above 122°C prevent the presence of hydrogen-consuming microorganisms. [8, and references therein] Others suspect that under favourable conditions, microbial activity drops off at a few hundred metres and that large reservoirs do exist at such shallow depths.

Natural hydrogen is usually found in a **mixture with other gases**, commonly nitrogen and methane. Natural hydrogen generated by radiolysis is often associated with helium. In geothermal systems, carbon dioxide and H_2S may be present. In active serpentinisation settings, conditions are highly alkaline and CO_2 is commonly removed from solution through carbonate precipitation and is therefore often absent or present only in minor amounts. In most reported occurrences, hydrogen concentrations are below 20 per cent. However, occurrences with hydrogen concentrations exceeding 80 per cent have been documented sporadically and, in rare cases, even surpassing 95 per cent.

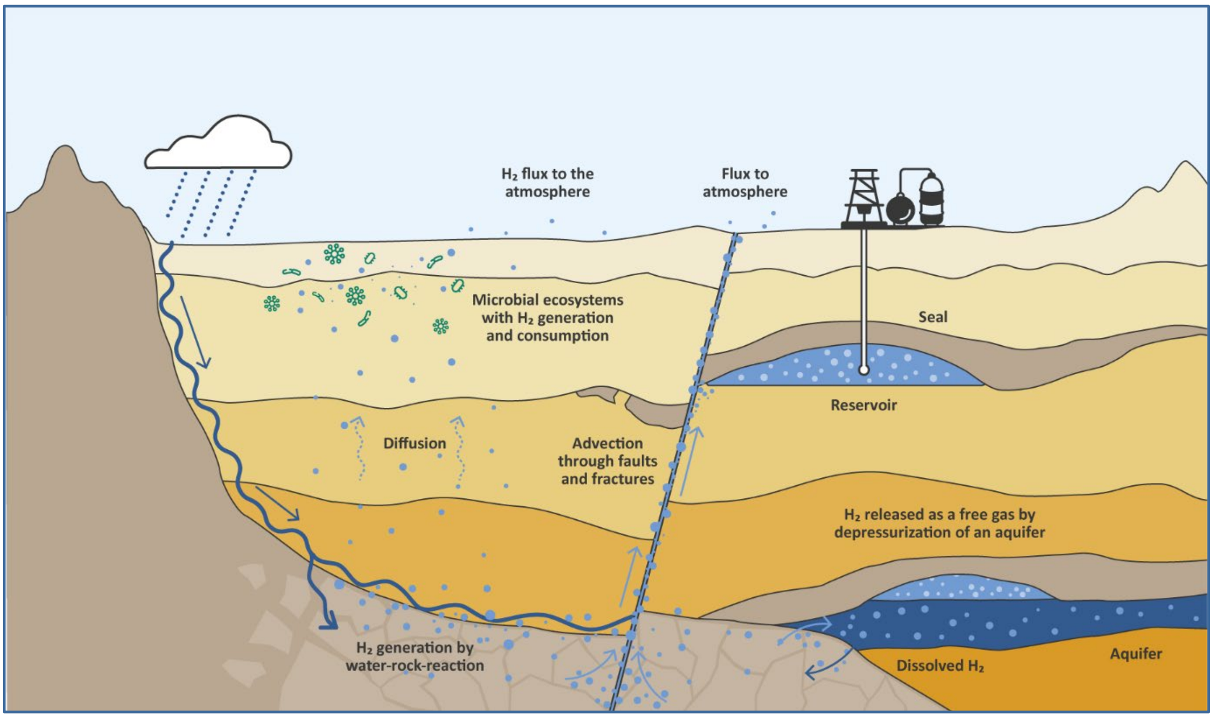

Figure 8: Schematic representation of natural hydrogen systems: generation, migration mechanisms, accumulation and consumption. Source: own illustration.

A.3 Quantitative estimates of natural hydrogen

Since there is no reliable data on natural hydrogen resources or reserves, estimated annual hydrogen generation and hydrogen leakage to the surface are often used as first-order indicators of global hydrogen potential. Estimates are based on aggregated data of measured hydrogen occurrences reported in the literature, and/or modelling. The annual hydrogen generation rate differs from the annual flow to the atmosphere by the share consumed by microbes and chemical reactions, by hydrogen being trapped in reservoirs and by leakage from reservoirs (see Figure 8).

Estimates of annual hydrogen leakage and annual generation in scientific literature vary widely. Based on a literature survey, the Royal Society estimates a global continental hydrogen leakage to the surface of up to 0.74 million tonnes per year. This estimate excludes volcanic gas flux, because it is unlikely to be commercially exploitable. [4] A much-noticed paper by Zgonnik based on reported hydrogen occurrences, that takes into account data from the former Eastern Bloc which previously received little attention, suggests a cumulative annual hydrogen flow of 23 million tonnes from all geological sources. [20] The paper has been criticised, however, for some double-counting. [4] It also includes hydrogen in the oceanic crust, which is unlikely to be economically exploitable. [4]

It should be noted that neither the annual hydrogen generation nor the annual leakage to the atmosphere are reliable indicators of the volume of natural hydrogen that could potentially be recovered from accumulated natural hydrogen systems. If continuously refilling short-term systems (see Section A.2) do exist, annual hydrogen generation and leakage rates would indeed be important indicators for their production potential. However, for long-term accumulation systems, the most important factor for potential commercial exploitation is how much hydrogen is trapped and preserved in accessible reservoirs. Based on a comprehensive literature review, the UK Royal Society concludes that the amount of hydrogen trapped in reservoirs cannot be quantified due to insufficient subsurface data and the limited number of well-documented discoveries.

A model approach to estimate the global natural hydrogen accumulations in the subsurface is presented by Ellis and Gelman. [10] Their results yield an in-place resource estimate ranging from a minimum of approximately 1,000 million tonnes to a maximum value seven orders of magnitude higher. The authors do not give an estimate of how much of this total resource would be accessible for exploitation. Annual hydrogen generation, which is an input parameter to the modelling calculations, ranges from 25 million tonnes per year to 25,000 million tonnes per year. The lower bound corresponds to previously published estimates such as those by Zgonnik. [20] The upper bound, however, incorporates speculative contributions from deep (mantle) sources. [10] The resulting annual flux to the surface ranges from 1 million tonnes per year to 1,000 million tonnes per year. The model allows to analyse the impact of parameters such as hydrogen generation, microbial consumption, and residence time of hydrogen on the resource quantity. However, the fact that both input parameters and resulting resources span multiple orders of magnitude emphasise the substantial uncertainties involved. Consequently, while the model explores possible scenarios, it does not permit robust conclusions regarding the resource potential of natural hydrogen.

A.4 Production costs

Only a few estimates of the production cost for natural hydrogen have been published. Some of these studies are based on existing reservoirs/wells while others are more generic and do not focus on existing sites. Gas composition, flow rate, well depth, delivery pressure, hydrogen purity, economy of scale and transportation emerge as parameters that affect costs strongly.

Musa et al. [49] estimate the cost of hydrogen production from a hypothetical sandstone reservoir in Australia at a depth of 1,000 metres. The hydrogen concentration is assumed to be 83 per cent, with the remainder of the gas being mostly nitrogen. A flow rate of 13,400 tonnes per year is recovered over a period of 30 years. Including hydrogen purification, the levelised cost of hydrogen result to USD 1.97 per kg. Note that this cost estimate refers to a very shallow reservoir, and greater depth is likely to increase the cost substantially.

Patonia et al. estimate production costs based on data from the test well in Bourakébougou, Mali. [48] For their calculation, they assume that larger deposits with similarly favourable conditions as in Bourakébougou – very high hydrogen concentration in a shallow reservoir (see Box Bourakébougou) – exist elsewhere. Their estimates range from USD 1.94 per kg for a flow rate of 2,880 tonnes per year to USD 5.51 for a flow rate of 480 tonnes per year. The assumed flow rates are 10 to 60 times those of the Bourakébougou field.

Subsequently to the study mentioned above, Lin et al. [50] used the data from the test well in Bourakébougou, Mali, to calculate the levelised cost of hydrogen (LCOH) and analyse transportation costs estimates. In their conclusion, they underline the importance of the parameters scale of operation and transportation costs. While they calculated a LCOH of USD 6.82 per kg with a production of 1.3 tons a day (about 475 tons/year), the LCOH could be reduced by more than 60% by scaling up the production to 8 tons/day (about 2920 tons/year). The transportation costs depend on the production scale, the distance to market, and the availability of infrastructure. For small-scale projects producing less than 6 tons per day (≈2190 tons/year) with no shared infrastructure, compressed hydrogen trucking is the only viable option, costing approximately USD 0.30– USD 2.50 per kg depending on the distance. Medium- to large-scale projects can take advantage of economies of scale, making dedicated pipeline infrastructure feasible and reducing costs to as low as USD 0.50 per kg for distances up to 500 km. For long-distance transport beyond 1,000 km, international shipping via ammonia carriers or liquefied hydrogen becomes cost-effective, with costs in the range of USD 2.00– USD 5.00 per kg, underscoring the importance of siting production near markets and leveraging shared infrastructure where possible. [50] It should be noted that transportation is an important cost factor for all types of hydrogen production, not only natural hydrogen. [114]

Mathur et al. [51] conducted a techno-economic analysis (TEA) of natural geological hydrogen and stimulated geological hydrogen. In contrast to the studies mentioned above, the analysis was not based on a specific existing well but on an analysis of similar processes, partly from natural gas processing and a set of assumptions. They analysed the different production processes while focusing mainly on the upstream processes of exploration, extraction and surface processing costs. The cost assumptions are based on data from analogues in the natural gas and geothermal industries. They neglected transportation costs due to the variability of cost estimates based on delivery distance and hydrogen throughput. For their analysis, they chose the following parameters: a hydrogen concentration of 75 per cent, a flowrate of 200 kg H_2/hour, a delivery pressure of 30 bar and a well lifetime of 20 years. According to their analysis, the production cost for natural geological hydrogen is estimated at USD 0.54/kg for natural hydrogen and USD 0.92 for stimulated hydrogen. They included a sensitivity analysis for these estimates in their analysis to identify the main cost drivers of the production process: gas concentration, flow rate, and delivery pressure. [51]

Zhang et al. [52] computed scenarios on the techno-economic viability of natural hydrogen from gas reservoir-type resources, focusing on the economic indicators of unit cost, net present value (NPV), and payback period. Their analysis included various values on six parameters: hydrogen purity, hydrogen volume, well depth, separation technique, number of production wells and the number of off-gas disposal wells. Their calculated production costs range from USD 0.14 to USD 5.33 per kg of H_2. They underlined the importance of hydrogen purity, stating that a purity of over 60 per cent helps decrease unit costs to between USD 0.14 and USD 3.05 per kg of H_2. [52]

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