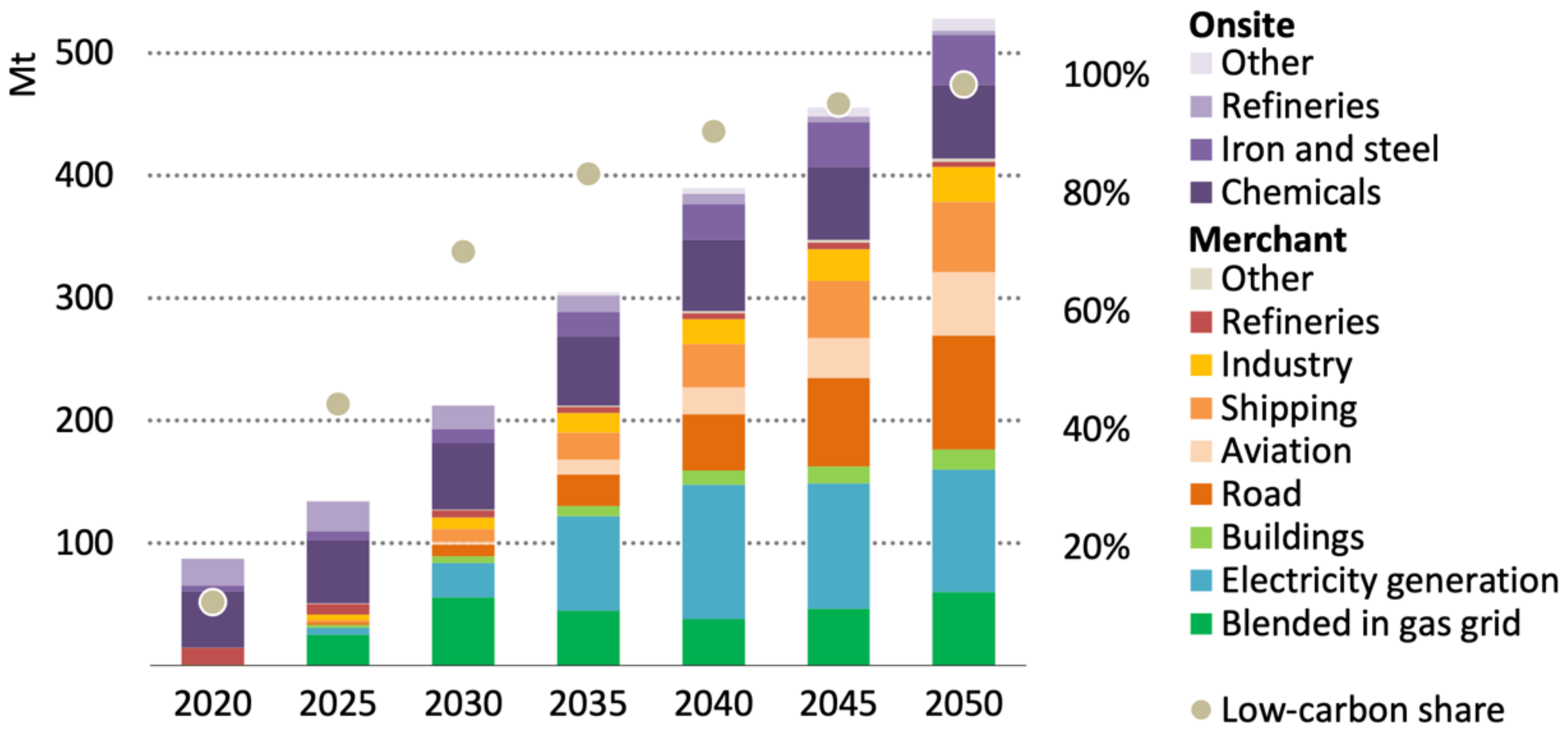
Science behind Natural Hydrogen and its Potential Application

Eiichi Setoyama

Hydrogen Use and Demand

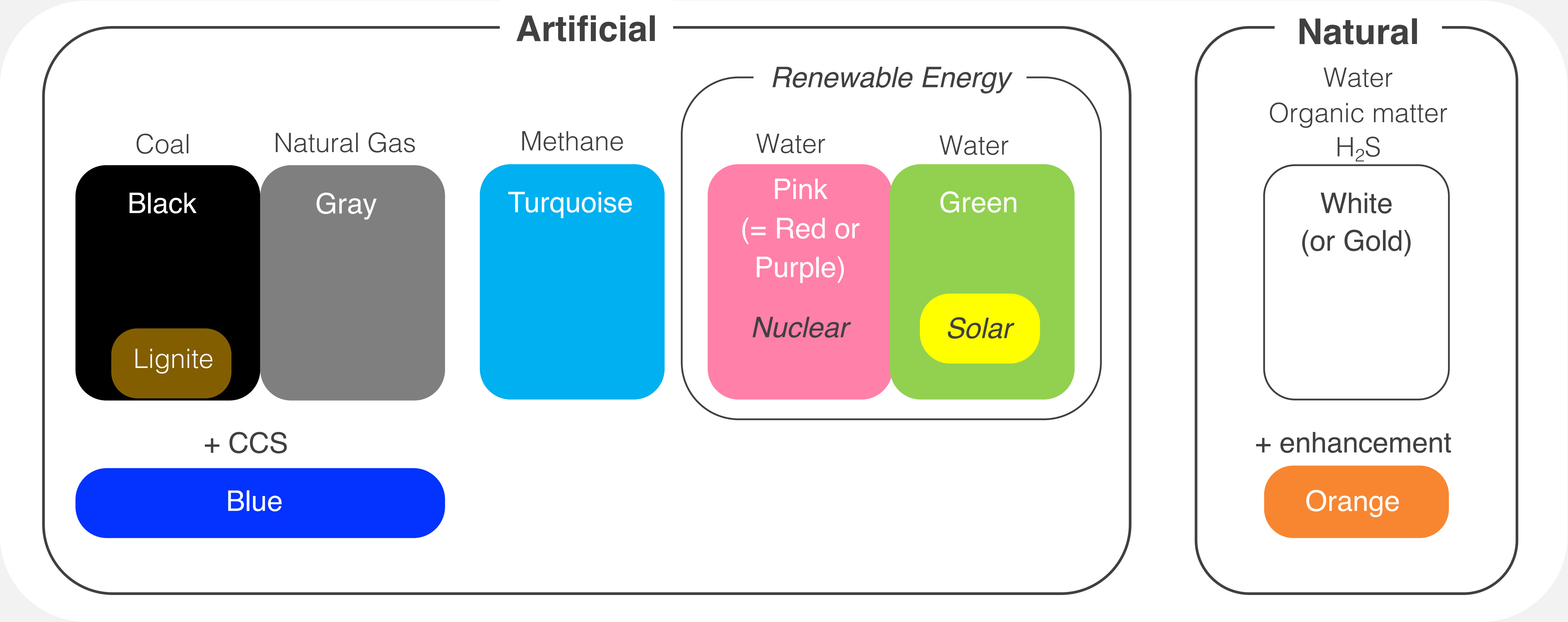
Figure 2.19 ▷ **Global hydrogen and hydrogen-based fuel use in the NZE**



NZE: Net-Zero Emission

From IEA (2021, Net Zero by 2050)

Sources of Hydrogen (Colors of Hydrogen)

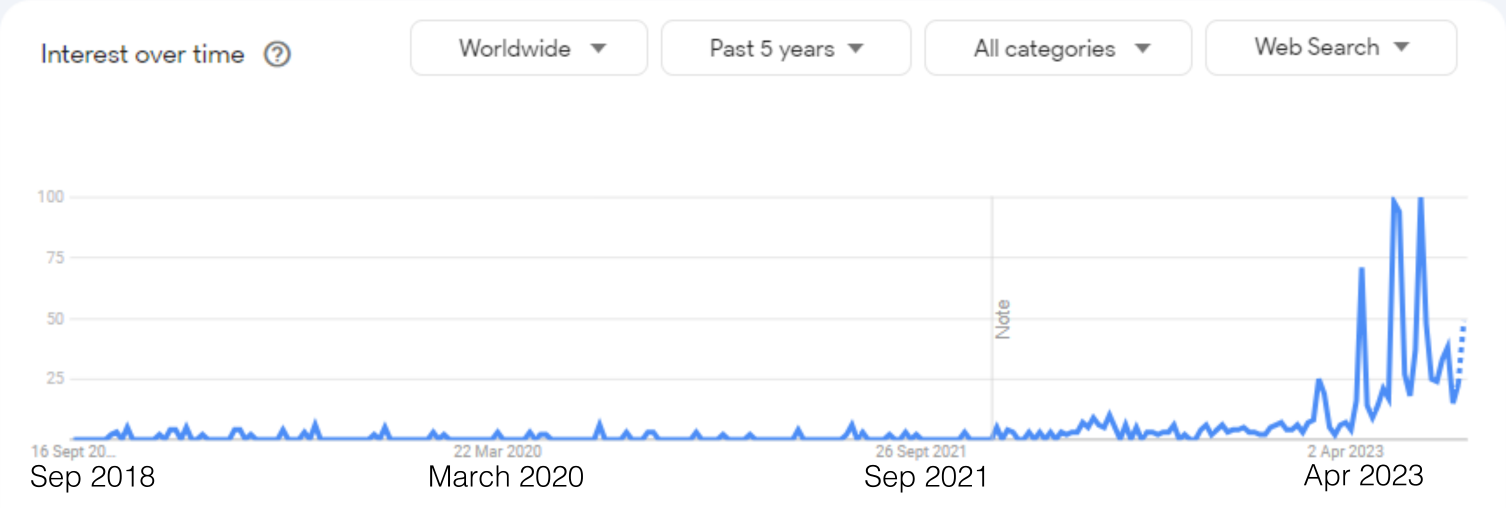


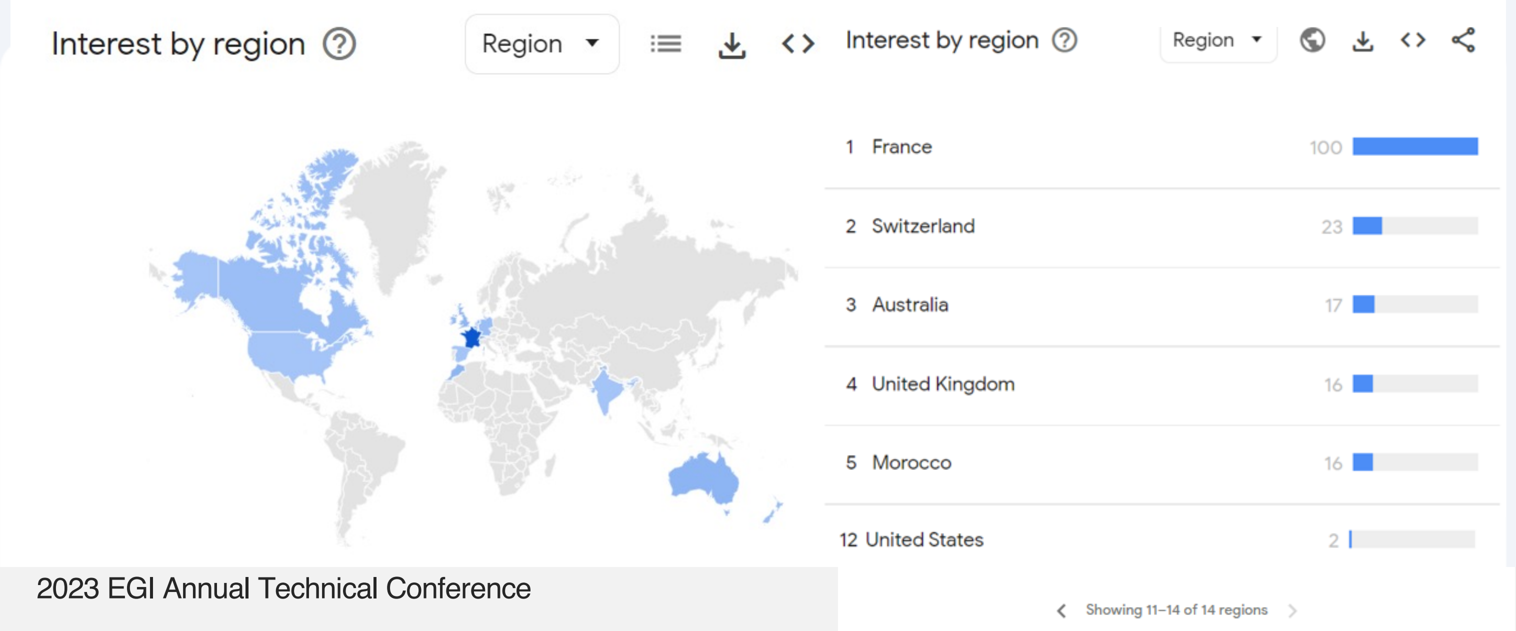
Low-emission H2: 0.7% in 2021
(IEA, 2022, Global Hydrogen Review)

Natural Hydrogen

Public interest (Google Trends)

Natural hydrogen
Topic





- Mali discovery (originally a dry water borehole in 1987; gas analysis in 2012)
- Prinzhofer et al. (2018) on the Mali discovery
- 1st hydrogen borehole in the US (2018)
- Zogonnik (2020, Earth-Science Reviews)
- “Hidden Hydrogen” in Science (Feb 2023)
- H-NAT2023 (Nov 2023, Australia)

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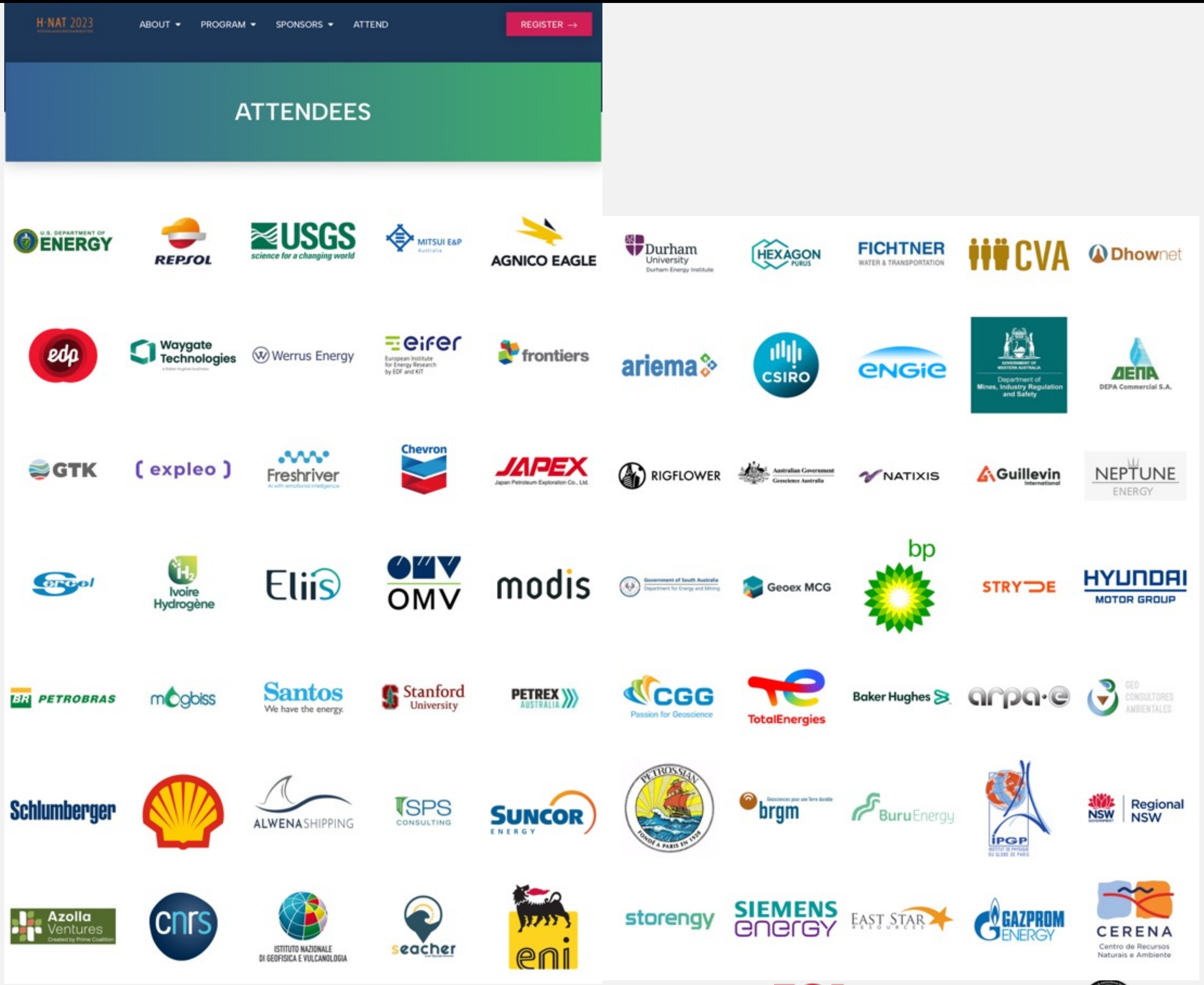

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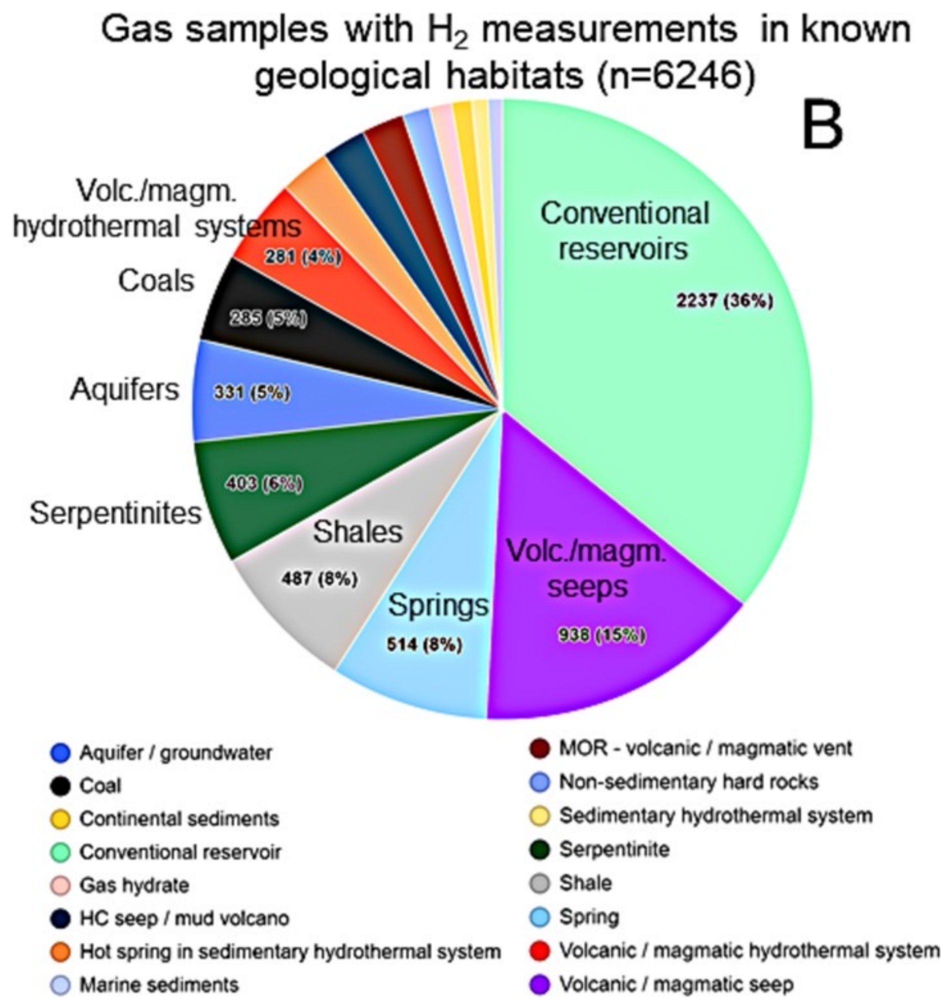
Natural Hydrogen

Natural Hydrogen (a.k.a. Native Hydrogen)

Naturally occurring hydrogen that is not produced through industrial processes

- includes **Geologic Hydrogen** found in subsurface



From Milkov (2022, Earth-Science Review)

High concentration of Natural Hydrogen reported from:

Ocean

- Mid-ocean ridge, Hydrothermal vents

Surface

- Volcanos, Seeps, Geysers

Subsurface

- Soil, Hydrocarbon reservoirs, Evaporite deposits, Aquifers, Crystalline basement, Mineral mines, Coal mines, Hydrothermal systems, etc.

Motivation behind Natural Hydrogen Research

Low Carbon footprint

- Yellow H_2 (Solar): **3.6 kg CO_2eq./kg H_2** (Kanz et al., 2021)
- Blue H_2 (SMR + CCS): **8.9 kg CO_2eq./kg H_2** (Lewis et al., 2022, NETL)
- Gray H_2 (SMR): **16.4 kg CO_2eq./kg H_2** (Lewis et al., 2022, NETL)

Low Water footprint (potentially)

- Blue H_2 (SMR + CCS): **24 litter/kg H_2** (NETL, 2022)
- Electrolytic H_2 (net zero USA): **10–80 litter/kg H_2** (Grubert, 2023)

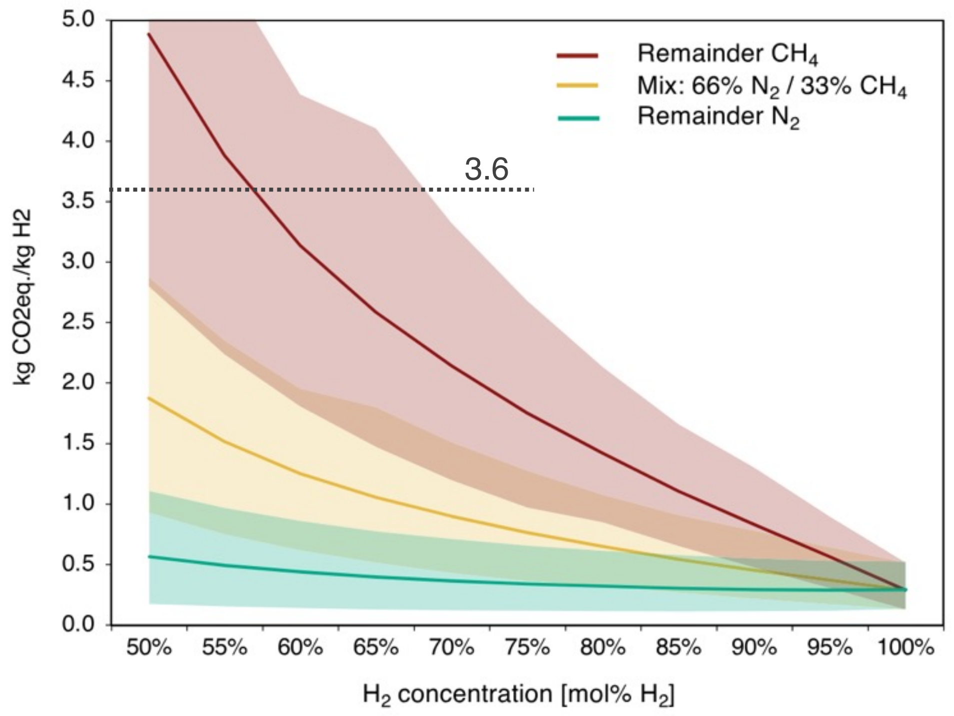


Figure 5. Variation in GHG intensity as a function of H_2 concentration, with remainder gas being either pure CH_4 (red), 66% N_2/33% CH_4 (yellow), or pure N_2 (green)

From Brandt (2023, Joule)

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Low Water footprint (potentially)

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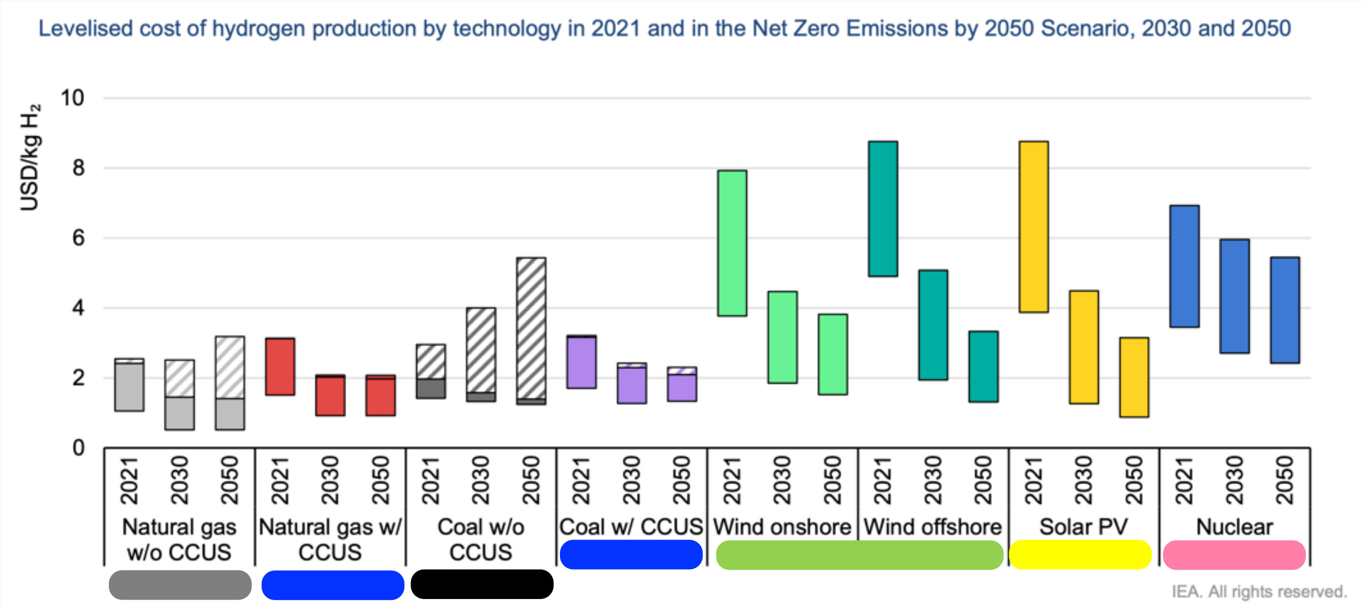
Cost

- Natural H_2: < \$1/kg H_2 (Gaucher et al., 2023, European Geologist)
- Blue H_2: \$1.64/kg H_2 (Lewis et al., 2022, NETL)
- Green H_2: \$5/kg H_2 (US DOE, 2021) to \$6/kg H_2 (Gaucher et al., 2023)



From IEA (2022, Global Hydrogen Review 2022)

Where and how much natural hydrogen?

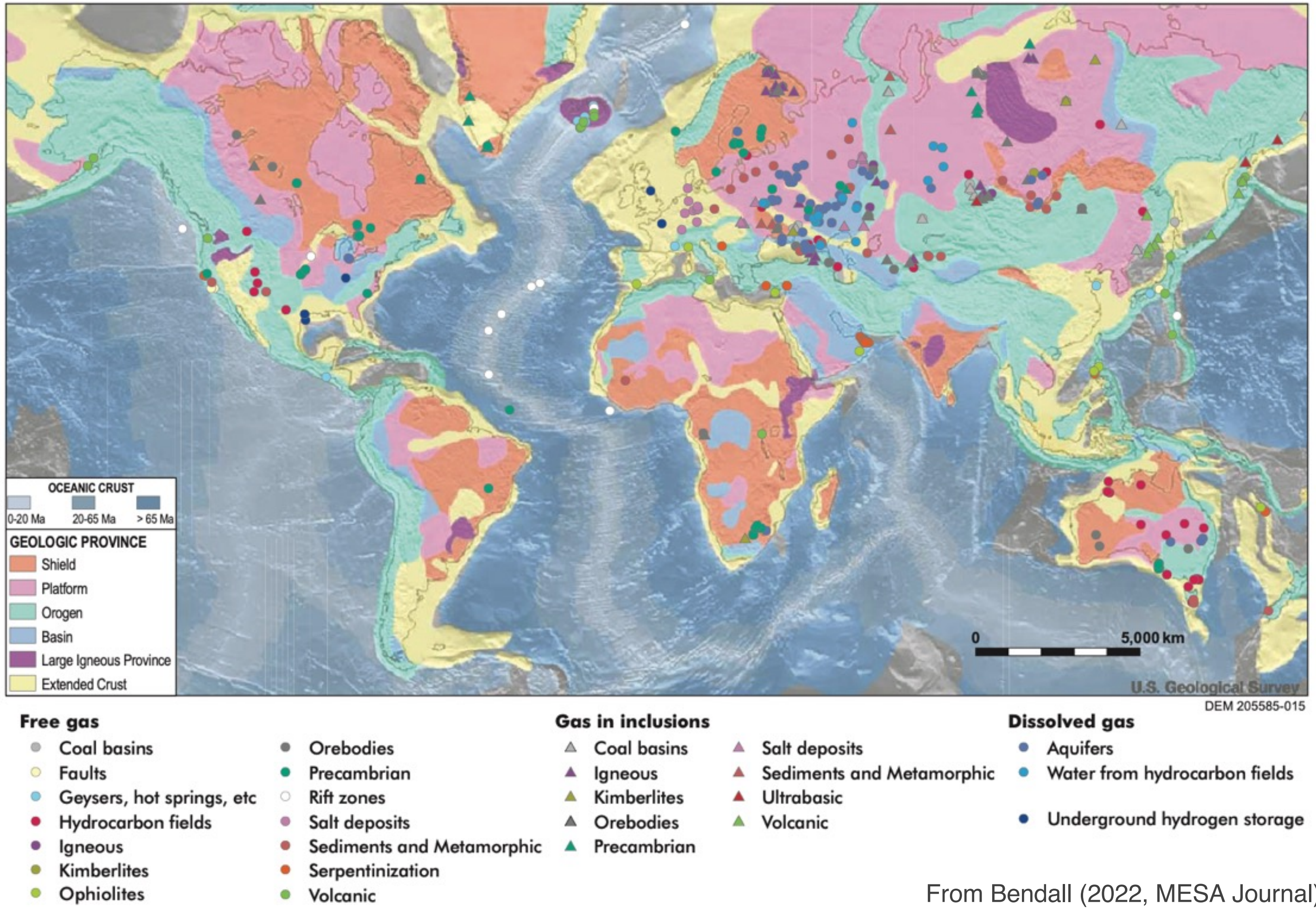
Global geologic hydrogen resource potential estimate using a box model (Ellis and Gelman, 2023, IMAGE2023 abstracts)

- 1,000s to 1,000,000,000 Mt of H_2 in place
- Mean value in 10s of million Mt of H_2 in place

  + 10s to 100s Mt of H_2/year

Local estimate examples

- 5 Mt of H_2 in the Bourakébougou field, Mali
- 1.3 Mt of H_2 in the Yorke Peninsula, Australia
- 5–10 Mt of H_2 in the Monzón field, Spain
- 46 Mt of H_2 in the Lorraine Basin, France

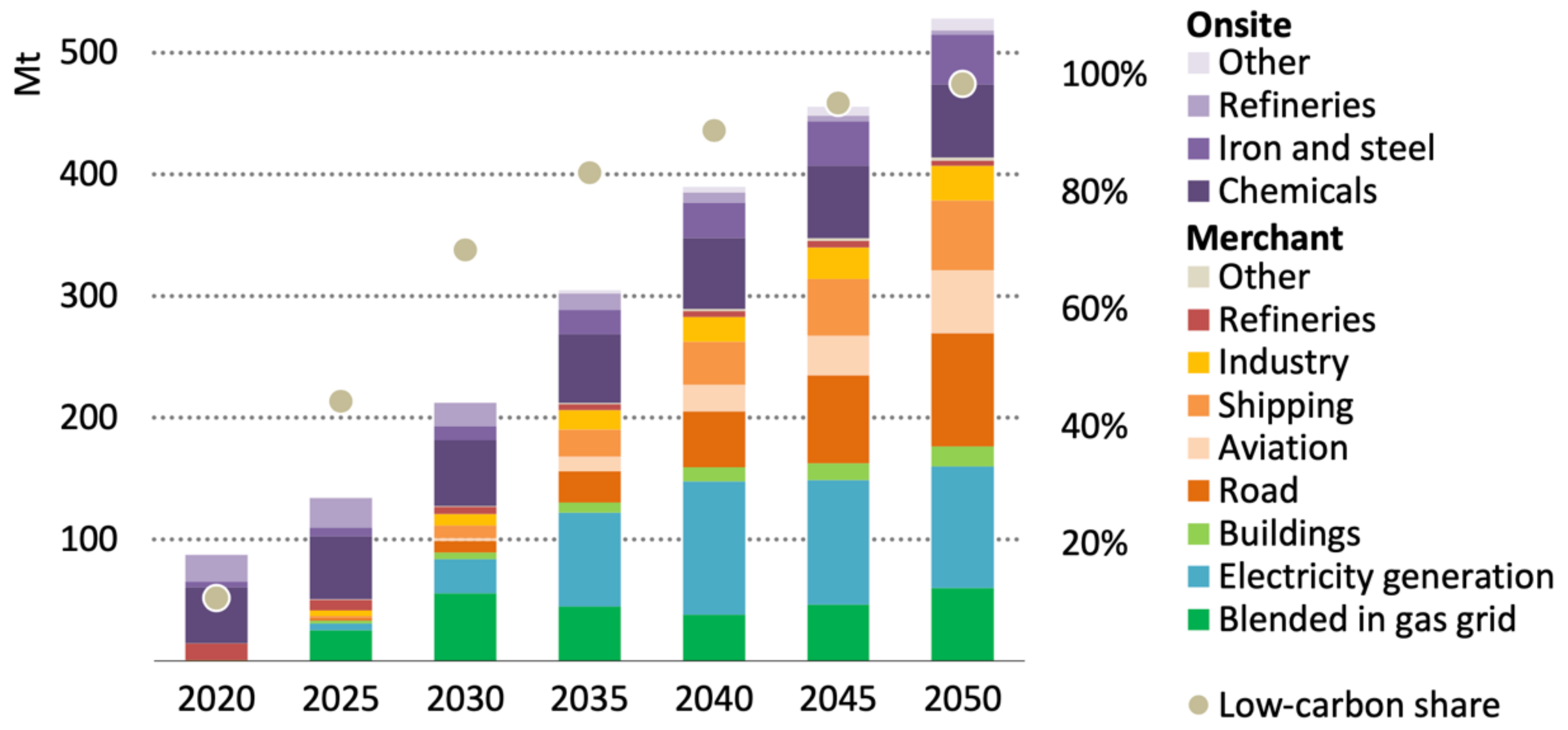


From Bendall (2022, MESA Journal)

Locations and geological environments of recorded hydrogen measured at >10% volume around the world.

Application of Natural Hydrogen

Figure 2.19 ▷ Global hydrogen and hydrogen-based fuel use in the NZE

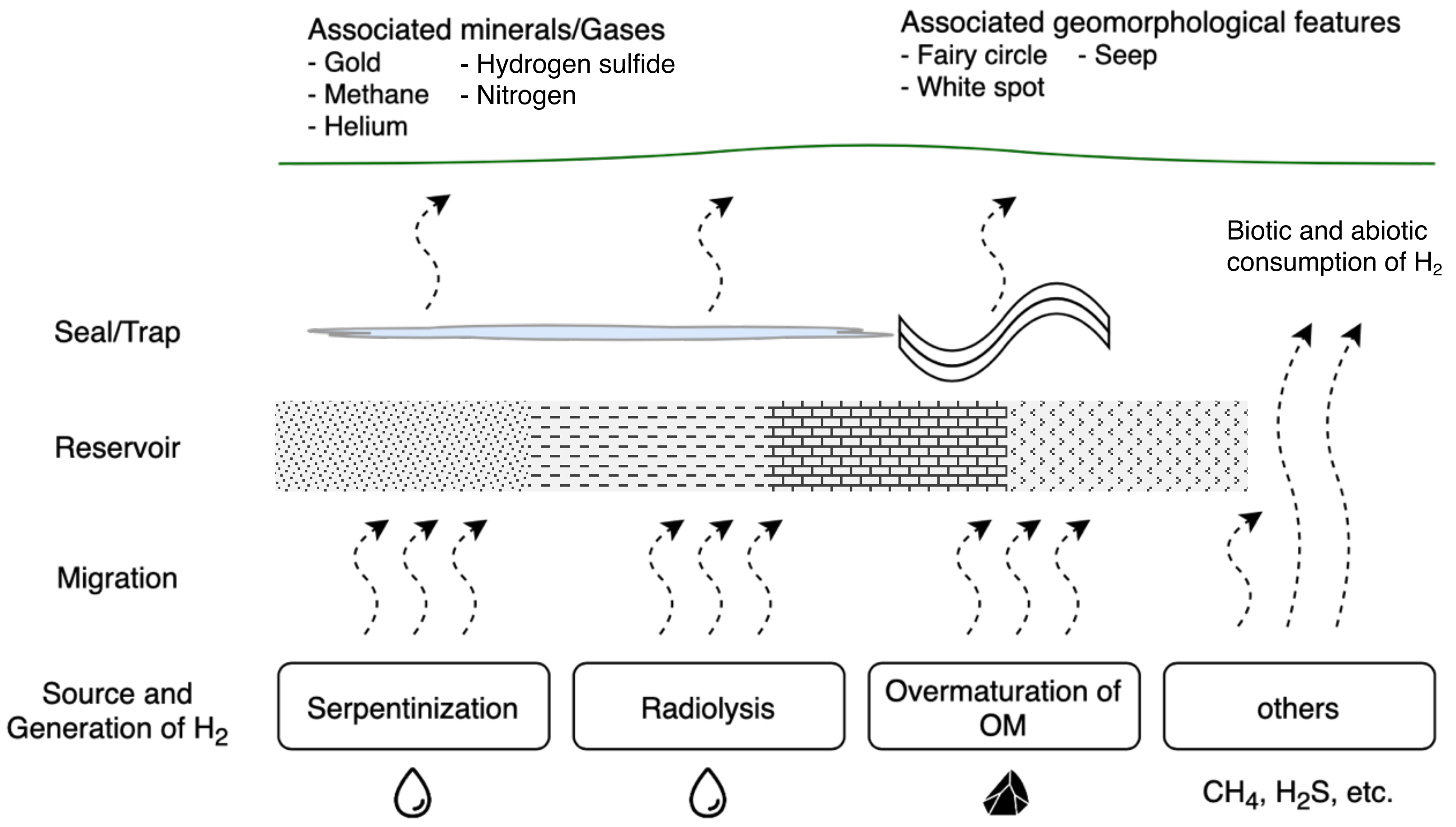


NZE: Net-Zero Emission

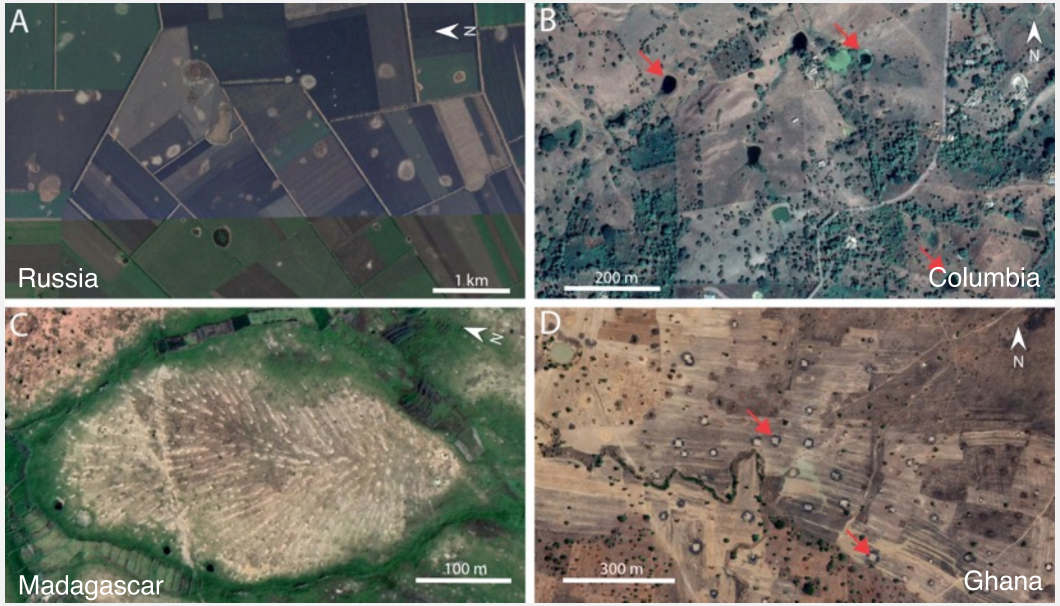
From IEA (2021, Net Zero by 2050)

Energy & Geoscience Institute AT THE UNIVERSITY OF UTAH

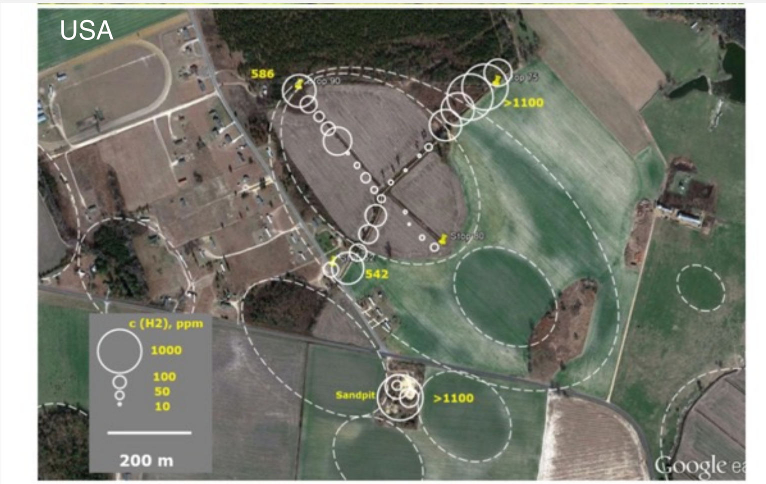
Natural Hydrogen Exploration



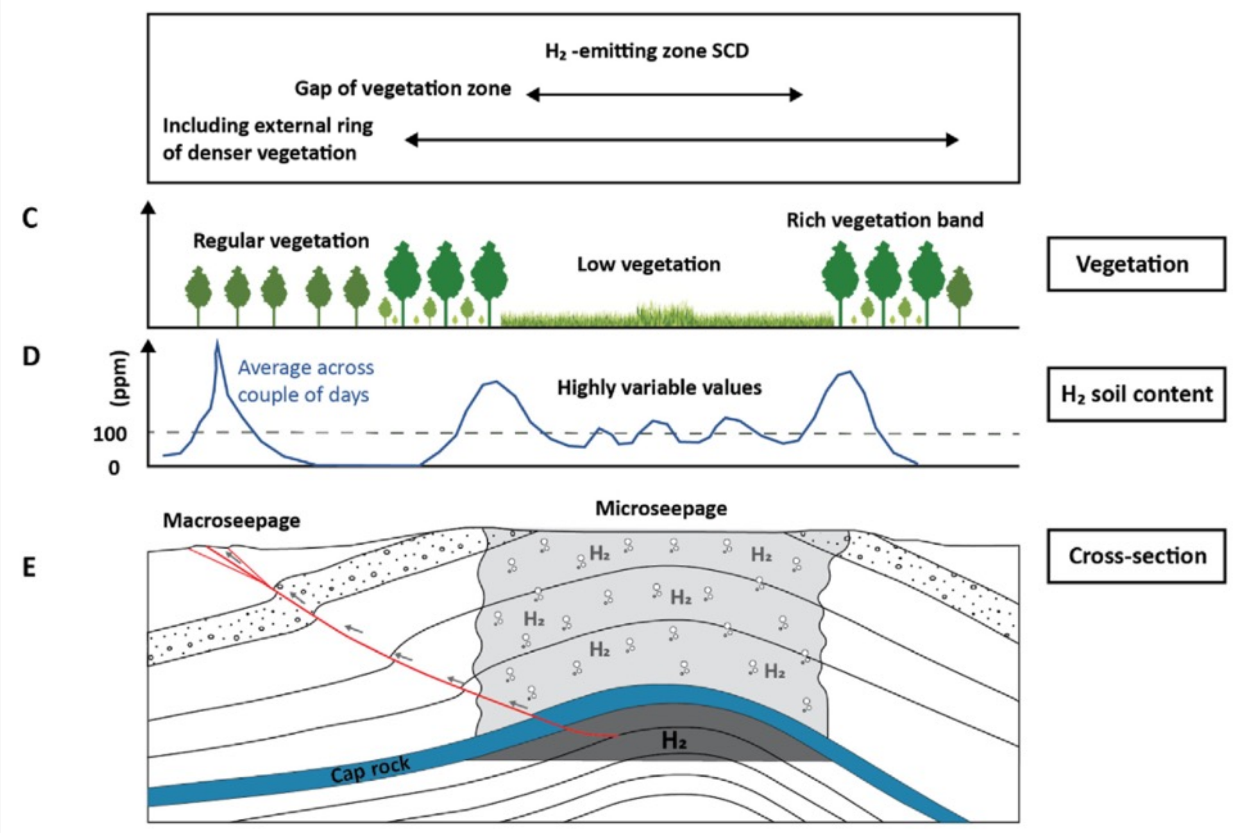
Natural Hydrogen Exploration: Seeps



From Malvoisin & Brunet (2023, Science of the Total Environment)



From Zgonnik et al. (2015, Progress in Earth and Planetary Science



Modified from Moretti et al. (2022, International Journal of Hydrogen Energy)

Natural Hydrogen Exploration: Source/Generation

Hydrothermal alteration

Water + Iron-rich rock + Heat

- Serpentinization of mafic–ultramafic rocks
- Hydration of siderite (sedimentary basins) and biotite in felsic rocks

Radiolysis

Water + U, Th, or K-rich rocks/evaporites

Mechanoradical generation

Water + Silicate minerals + Faults (orogenic belts, continental rifts, etc.)

Degassing of magmas

Water + Hydrogen sulfide

Oxidation of magnetite to hematite

Water + Banded iron formations

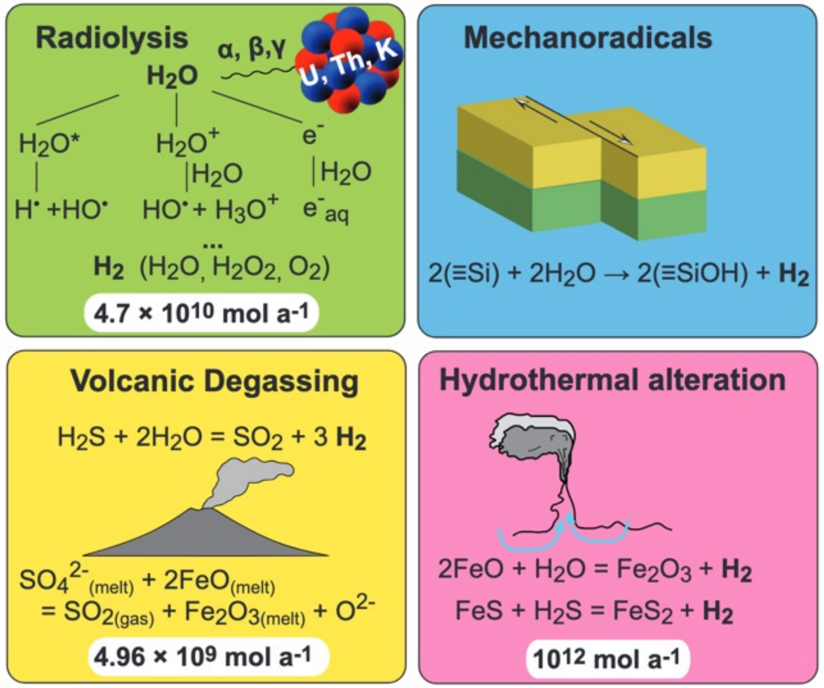
Overmaturation of organic matter

Organic matter + Heat (Ro > 3.5%)

Deep-seated hydrogen from the Earth's core and mantle

Stored in the mantle and core

Not produced in the mantle or the crust by chemical reactions



From Klein et al. (2020, Elements)

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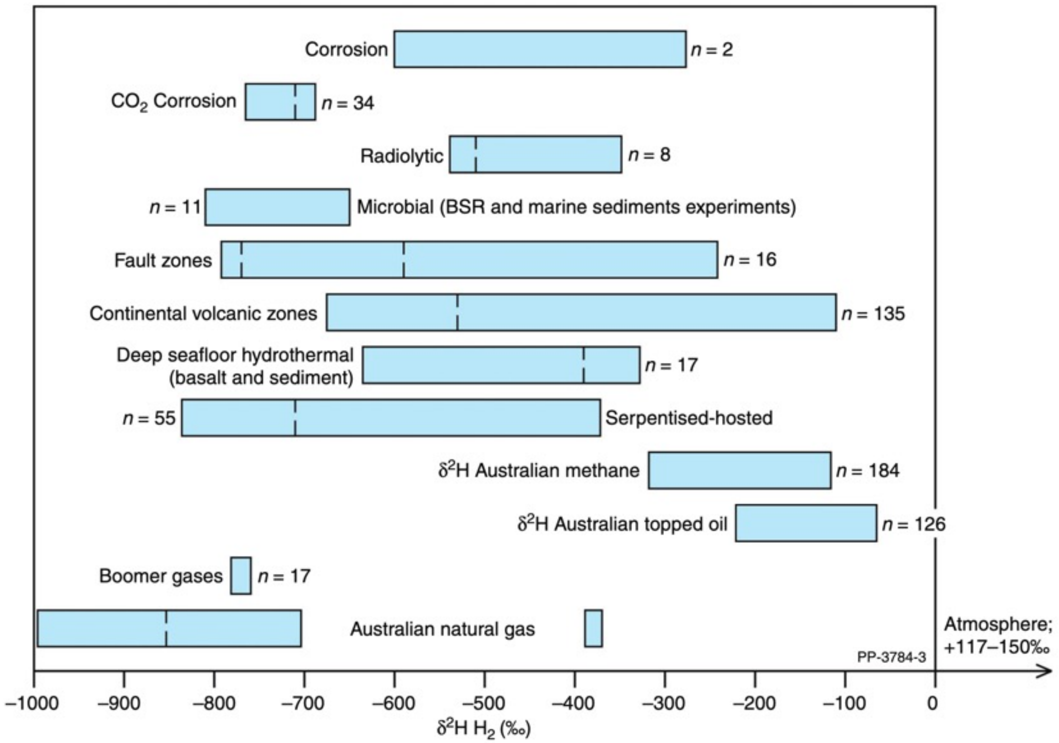


From Boreham et al. (2021, APPEA Journal)

Exploration targets: Basement areas with Fe-rich and/or uranium-rich rocks, such as Precambrian continental crust

Natural Hydrogen Exploration: Migration

- Diffusion and Advection
- Fractures and Faults as conduits
- High solubility of H_2 at depth
  - Long-distance migration as solute is also possible

Biotic and abiotic consumption of hydrogen

- Biotic: Methanogens (CH_4), Sulfate reducers (H_2S); Homoacetogens (CH_3COOH), Iron reducing bacteria (Heinemann et al., 2021, Energy Environ. Sci.)
- Abiotic: Redox reactions with Fe-bearing minerals, H_2S production, CH_4 production, through HC formation

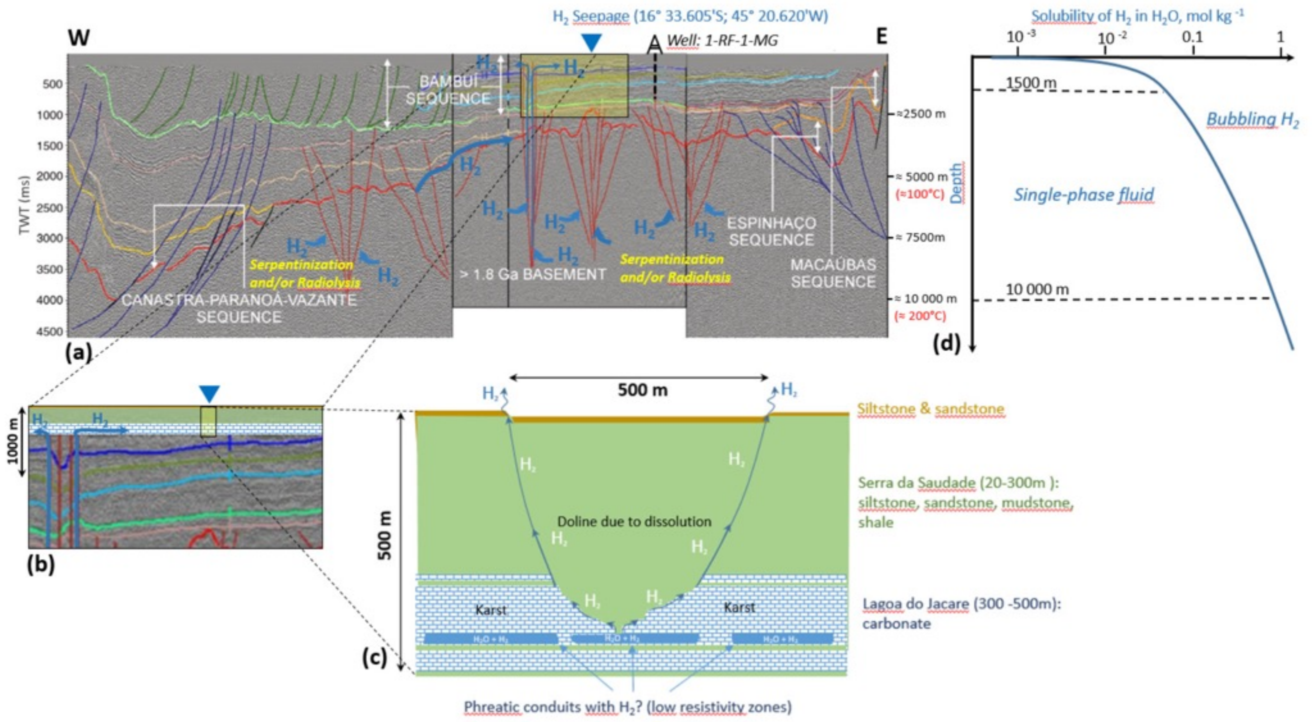


Figure 7. Conecputal model of the H_2 cycle in the Sao Francisco Basin. (**a**) Interpretated seismic section (Martins-Neto, 2009). (**b**) Zoom of the upper part of the Bambui sequence. (**c**) Possible presence of a karst structure according to the presence of sinkholes (Figure 2). (**d**) Calculated solubility of H_2 in H_2O vs. depth (Bazarkina et al., 2020 [59]).

From Donzé et al. (2020, Geosciences)

Exploration targets: Deep faults

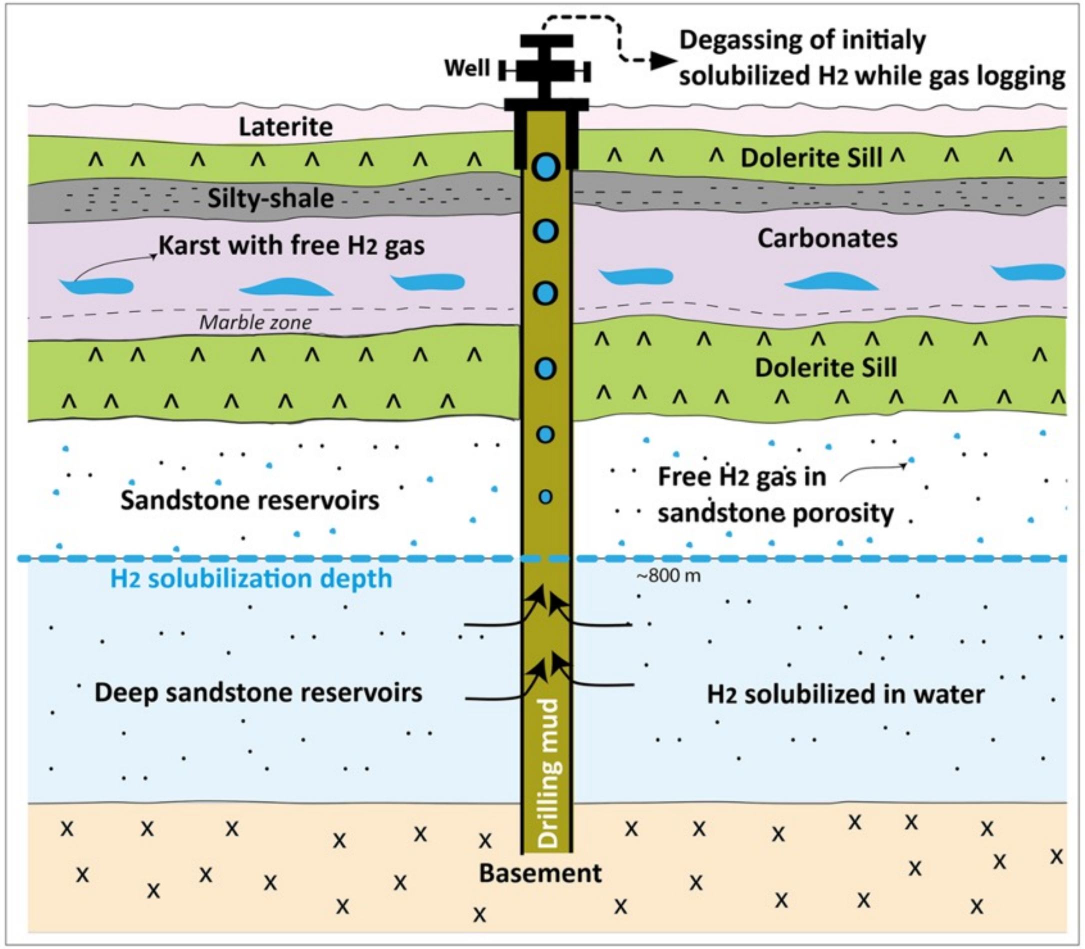
Natural Hydrogen Exploration: Reservoir and Seal

Seal/Trap

- Aquifers
- Igneous/metamorphic rocks
- Evaporite layers (e.g., Monzó-1, Spain)
- Clay (Athabasca, Canada)

Reservoir

- Sandstone
- Siltstone
- Igneous/metamorphic rocks
- Evaporite layers
- Carbonate rocks



Bourakébougou field, Mali

From Bendall (2023, Scientific Reports)

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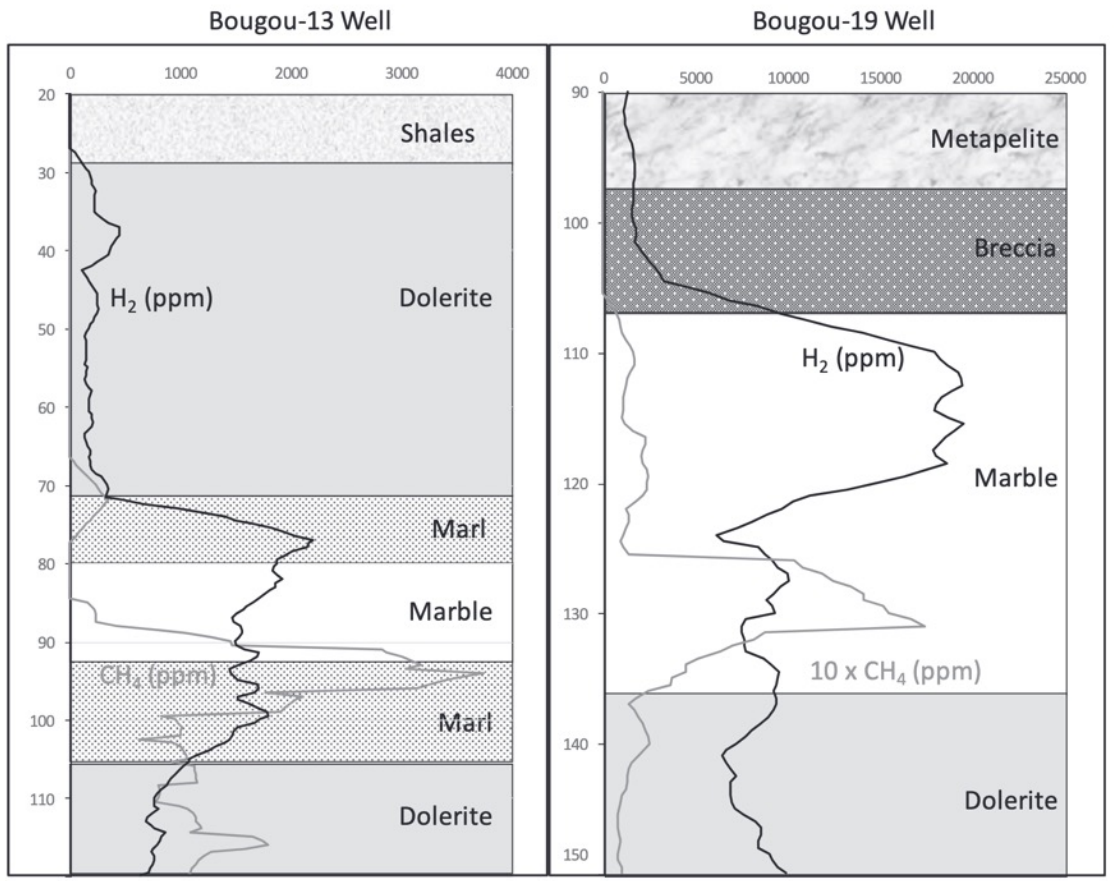


From Prinzhofer et al. (2018, International Journal of Hydrogen Energy)

Bourakébougou field, Mali

Exploration/Production Technology Readiness Level

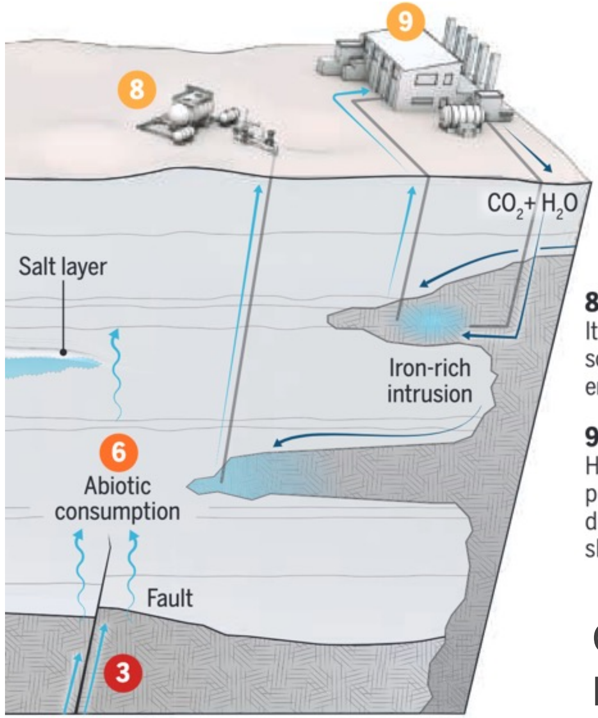
TRL Native H_2 Exploration/Production

0 Discovery of H_2 at the Earth surface Discovery of Natural Hydrogen	Done
1 Systematic research of H_2 seepages in various environments Research on seeps	Done
2 Short time monitoring of sites Short-time monitoring of sites	Done for 2-3 sites
3 Understanding of the origin of H_2 Understanding of Source	Done for 2-3 sites
4 Small Scale prototype of permanent H_2 fluxes / Numerical modelling of the H_2 permanent seepages Global understanding of the Hydrogen system Natural hydrogen systems	In Progress in Academia
5 Median Scale prototype (1200 m) Perennial production of a demonstrator over several years Production over several years	Hydroma (Mali)
6 First deep borehole (3000 – 5000 m) 1st deep boreholes (3000–5000 m)	Natural hydrogen energy LLC Desert Mountain Energy
7 First Exploration plan at regional scale First delineation / Several boreholes Regional scale exploration	In progress Santos (Australia)
8 Prototype of Production of the first discovery Porto-type large-scale production	No
9 Scaling-up / Commercial exploitation Commercial exploration	No

Modified from Gaucher et al. (2023, European Geologist)

Figure 1: Evaluation of the technology maturity using the Technology Readiness Levels (TRL) method.

Enhancing Natural Hydrogen Production



8 Direct
It might also be possible to tap the iron-rich source rocks directly, if they're shallow and fractured enough to allow hydrogen to be collected.

9 Enhanced
Hydrogen production might be stimulated by pumping water into iron-rich rocks. Adding carbon dioxide would sequester it from the atmosphere, slowing climate change.

Chemical, Biological, Mechanical, Thermal, etc.

From Hand (2023, Science)

ET G Category 1. Stimulation
The proposed model must be able to do one or more of the following:

1a. Increase reaction rate by *>10^5×* over the rate found in the native ore being evaluated at an equivalent starting *T* and *P* (generic rate reported as 5×10^4 kgs^{-1} for 1 km^3).[113]

1b. Increase the rate of other target H_2 producing mineralogical processes to produce a *comparable amount of H_2 to **1a**.*

U.S. Department of Energy Announces $20 Million to Explore Potential of Geologic Hydrogen

ARPA-E Unveils Two Initiatives Focused on Low-Cost, Low-Greenhouse Gas Emissions Hydrogen Production

09/07/2023

Exploratory Topics (DE-FOA-0002784)

Production of Geologic Hydrogen Through Stimulated Mineralogical Processes

Topic Issue Date	September 7, 2023
Deadline for Questions to ARPA-E-CO@hq.doe.gov	5 PM ET, October 13, 2023
Submission Deadline for Full Applications	9:30 AM ET, October 24, 2023

A. Topics of Interest

The following is a non-exhaustive list of technologies that are of interest for ET G. Applications can address one or more technologies:

- *Stimulation and generation*: Technologies which enhance the natural rate of serpentinization or other equivalent hydrogen producing geochemical reactions (*e.g.*, reduction of iron bearing minerals in banded iron formations, clinkers).
- *Modeling approaches:* Methods and tools to predict the viability of subsurface resources for stimulated hydrogen generation, inform reservoir management, or assist with stimulation efforts.
- *Characterization:* Methods and tools to map subsurface and ocean floor resources (*e.g.*, ultramafic formations or other candidate formations) and quantify physiochemical properties of interest, specifically total Fe content, Fe(II) concentration, Fe(II)/Fe(III) ratio, specific surface area, permeability, or other parameters relevant to stimulated hydrogen generation.

Summary

- Demand for Hydrogen
- Application of Natural Hydrogen
- Natural Hydrogen System and Exploration

Next steps

- Natural Hydrogen layers on EGICONNECT (publicly available) by the end of 2023
- Natural Hydrogen updates on EGI LinkedIn account
- EGI Living Atlas of Natural Hydrogen (GIS + Wiki)

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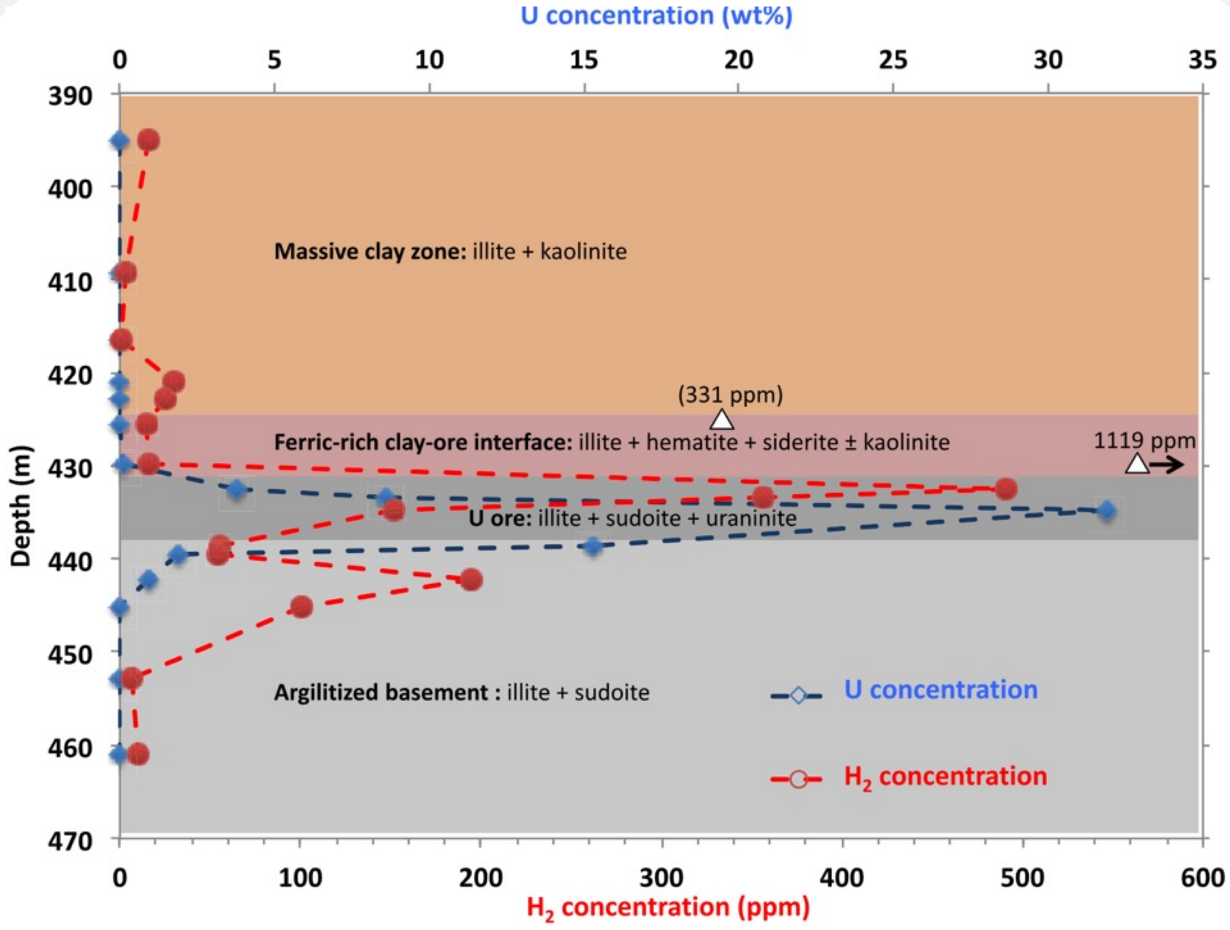

Athabasca, Canada From Truche et al. (2018, Earth and Planetary Science Letters)

Exploration targets: “Traditional”+ Ignerous/metamorphic rocks and aquifers