



THE OXFORD
INSTITUTE
FOR ENERGY
STUDIES

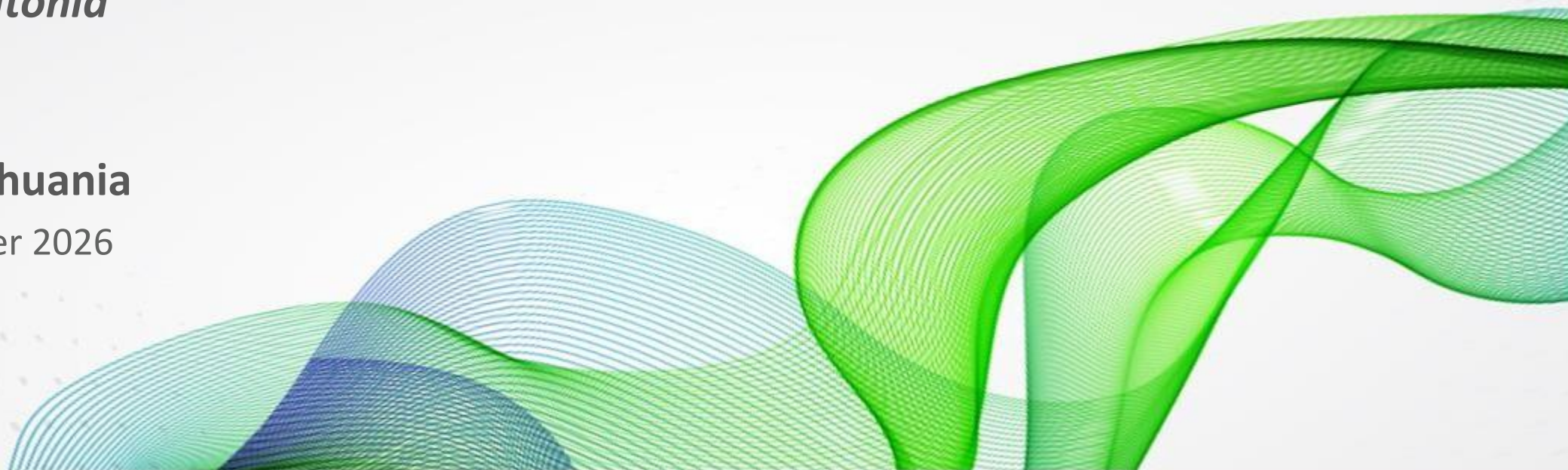
Natural (geologic) hydrogen and its potential role in a net-zero carbon future

Aliaksei Patonia

ET FORUM

Vilnius, Lithuania

18 September 2026

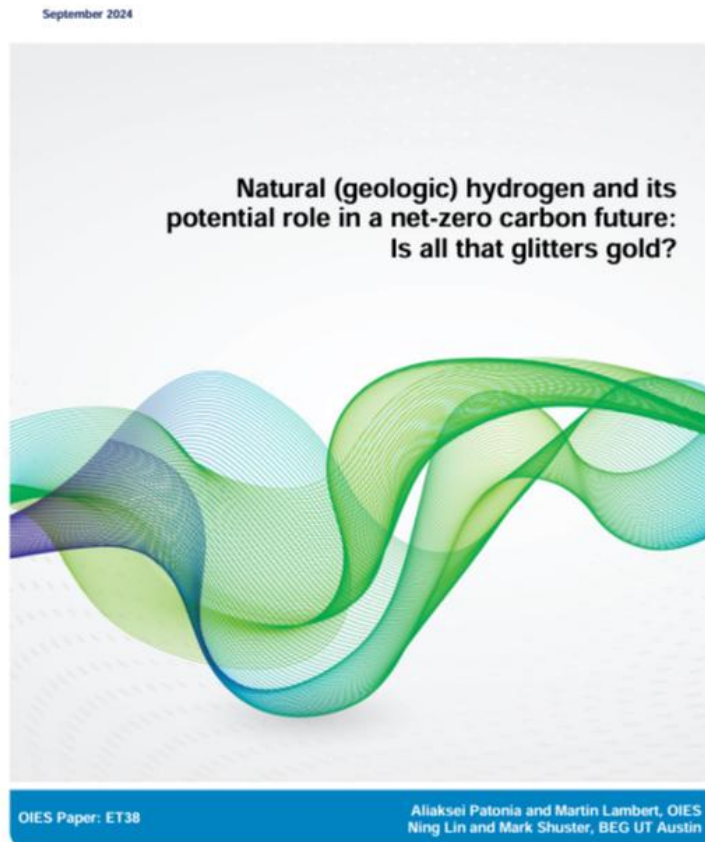


Aliaksei Patonia and Martin Lambert, OIES
Ning Lin and Mark Shuster, BEG UT Austin

OIES ENERGY TRANSITION RESEARCH



Our publications



Natural hydrogen techno-economics and valuation

Ning Lin^{a,1,*}, Aliaksei Patonia^b, Mark Shuster^a, Martin Lambert^b, Tongwei Zhang^a

^a Bureau of Economic Geology, University of Texas at Austin, 10100 Burnet Rd, Austin, TX 78758, USA

^b Oxford Institute for Energy Studies, 57 Woodstock Road, Oxford, OX2 6PA, Oxfordshire, UK

HIGHLIGHTS

- First techno-economic analysis of natural hydrogen production using the Bourakéhougon Field as an illustrative case.
- Evaluates the levelized cost of hydrogen (LCOH) for natural hydrogen production under scaling scenarios and cost uncertainty.
- Scaling production significantly reduces LCOH by over 60%.
- Policy incentives can further reduce breakeven costs, potentially approaching \$1/kg.
- Transportation costs drive commercial feasibility, varying from \$0.30 to \$5.00/kg.

ARTICLE INFO

Keywords:
Natural hydrogen
Techno-economic analysis
Levelized cost of hydrogen (LCOH)
Hydrogen production economics
Commercialization
Energy transition

ABSTRACT

Natural hydrogen, often referred to as “white” and sometimes “gold”, has recently emerged as a potentially compelling low-carbon energy resource with significant global decarbonization potential. This study presents a techno-economic analysis using a hybrid approach: it models hydrogen production based on test-well data from the Bourakéhougon field in Mali—an ideal reference case due to its high purity and shallow depth, allowing for an assessment of economic potential under favorable geological conditions, while applying a capital and operational cost structure benchmarked against the U.S. Gulf Coast. The estimated levelized cost of hydrogen (LCOH) in a scaled production scenario of 1.3 tons/day across ten vertical wells is \$0.82/kg, and it could decrease to \$2.40/kg as the scale of production increases to sixty wells without diminishing returns of production. The analysis further demonstrates that these costs are highly sensitive to long-term reservoir performance to complement the constant production rate assumption in the base case. A simplified production decline scenario illustrates an increase in the LCOH by nearly 70%. Besides scale optimization, policy incentives can significantly reduce the LCOH to competitive levels close to \$1.00/kg compared to conventional hydrogen production. This study further highlights that uncertainties in resource viability from exploration risks and transportation costs greatly affect the commercial viability of natural hydrogen production.

1. Background

Hydrogen has long been recognized as a versatile industrial gas, primarily used in oil refining, the production of fertilizers, and the chemical industry. Until very recently, the consensus has been that hydrogen is rarely found on Earth in its pure form at scale [1], and most of it has to be manufactured from fossil fuels such as natural gas, oil, or coal [2] with significant carbon dioxide (CO₂) emissions. There has been renewed interest in hydrogen due to its potential role in decarbonizing the global energy system, driven by the emergence of low-carbon production

pathways and advancements in carbon capture and storage technology in post-production processes [3].

Table 1 summarizes the generation pathways of hydrogen production based on the feedstock and production technologies used. The table focuses on the production mechanisms and estimated carbon intensities, while these pathways are often referred to using a color wheel terminology for simplicity in the literature. For example, gray hydrogen corresponds to steam methane reforming (SMR) of natural gas without carbon capture, and brown hydrogen refers to hydrogen produced from

* Corresponding author.

E-mail address: Ning.Lin@beg.utexas.edu (N. Lin).

¹ This research was supported by GeoH2, an industrial affiliates program (IAP), conducts geoscience, engineering, and economic research at the Bureau of Economic Geology.

<https://doi.org/10.1016/j.apenergy.2026.127406>

Received 26 June 2025; Received in revised form 30 December 2025; Accepted 8 January 2026

Available online 16 January 2026

0306-2619/© 2026 Published by Elsevier Ltd.



Most common/ previous assumptions about natural hydrogen

- Although hydrogen is the most abundant element in the universe, until recently **it has been believed to rarely occur in pure form on Earth**
- Although millions of oil and gas wells have been drilled worldwide, **hydrogen above trace levels (>~1%) reported in only a few dozen fields**
- **Hydrogen** migrating upward through thermally mature organic-rich rocks **is likely consumed by hydrocarbon forming reactions**
- Hydrogen is very diffusive and reactive (both biologic and abiotic reactions) and therefore **economic accumulations of hydrogen were considered to be very unlikely to form**

Then why are there so many H₂ shows?

Surface observations of high hydrogen concentrations (>10%)



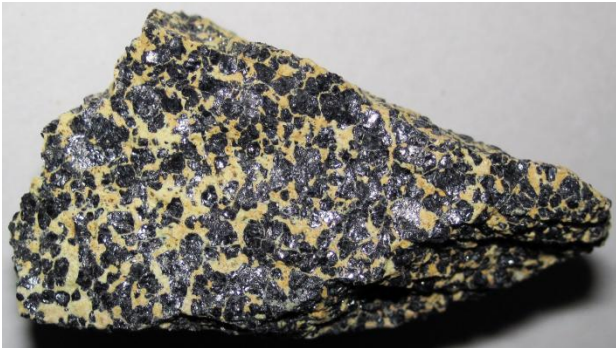
Source: Adapted from Zgonnik (2020)



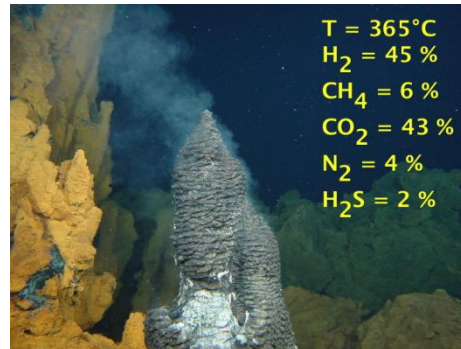
Current assumptions, hypotheses, estimates

- Oil and gas exploration **has not been targeted at hydrogen**
- **Hydrogen not analysed in natural gases** in most cases
- **Geologic settings** where hydrogen generation is most likely to occur **are not where oil and gas is found:**

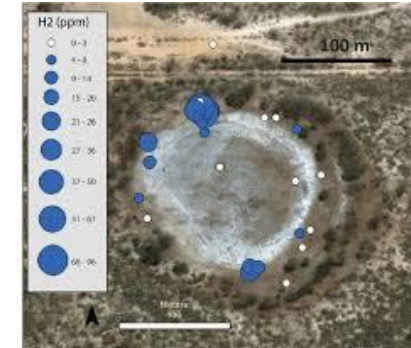
a) ophiolites,



b) mid-ocean ridges,



c) cratons, etc.



- **Mineral exploration generally does not look at gas composition** and is typically **much shallower** than the probable locations for hydrogen accumulations
- Hydrogen is the smallest molecule and that is why it is **hard to track and sample it**
- But most importantly... perhaps, ***we haven't been looking for hydrogen in the right places with the right tools?***
- **“There are trillions of tonnes of naturally occurring hydrogen in underground reservoirs, a tiny percentage of which would meet all the world's H₂ needs for hundreds of years”** (Unpublished report by USGS)



The new gold rush?

Hydrogeninsight

Production

'Natural hydrogen will be the next shale, and we'll make it for \$1/kg': explorers

Start-ups are bullish that history will repeat itself and bring cautious energy incumbents into geologic H2

FRANCE 24

Home Shows News Live

France Africa Middle East Americas Europe Asia-Pacific

Shows / People & Profit

Natural hydrogen: The new gold rush?

Issued on: 21/03/2024 - 13:19 Modified: 21/03/2024 - 13:21

FINANCIAL TIMES

JS COMPANIES TECH MARKETS CLIMATE OPINION LEX WORK & CAREERS LIFE & ARTS HTSI

Hydrogen power + Add to myFT

Geologists signal start of hydrogen energy 'gold rush'

Natural sources of the gas are more abundant than expected and could supply energy needs for centuries, study shows

SUSTAINABLE FUTURE

A global gold rush for buried hydrogen is underway — as hype builds over its clean energy potential

PUBLISHED TUE, MAR 26 2024 2:17 AM EDT

Sam Meredith @IN/SAMUELMEREDITH @SMEREDITH19

Science

HIDDEN HYDROGEN

Does Earth hold vast stores of a renewable, carbon-free fuel?

16 FEB 2023 • 2:00 PM ET • BY ERIC HAND

upstream

Hydrogen

'There is enough natural hydrogen underground to meet all demand for hundreds of years', says US government agency

Geologists expect 'gold rush' for natural hydrogen resources, conference told

Science

News Home All News Scienceinsider News Features DONATE

Gusher of gas deep in mine stokes interest in natural hydrogen

Flow of clean-burning fuel in Albanian mine dwarfs rates of other seeps

BBC

Home News Sport Business Innovation Culture Travel Earth Video Live

Could there be a gold rush for buried hydrogen?

12 December 2023

By Emma Woollacott, Technology of Business reporter

E&ENews

By POLITICO

ENERGYWIRE

Lawmakers study geologic hydrogen's promise, obstacles

By Christian Robles | 02/29/2024 06:24 AM EST



Key forms of naturally occurring hydrogen

- **Hydrogen dissolved in water** (ground water and water from oil and gas fields): Low H_2 content, not an economic resource

For instance, for the average H_2 content of $520.8 \text{ cm}^3/\text{l}$, you'd need to produce $>21,000 \text{ l}$ for each 1 kg of H_2 at atmospheric conditions. Assuming other gases in solution, the H_2 would need to be separated as well.

- **Hydrogen in inclusions** (igneous, sedimentary, ultrabasic rocks): Volumetrically insignificant, not a hydrogen resource

Heating and melting minerals for the extraction of H_2 will destroy the hydrogen we need

- **Hydrogen as a free gas** (tectonic features, gas seeps/ vents, rocks, deposits): Potential hydrogen resource

Suggested origin: Serpentinisation, radiolysis, thermal decomposition, coalification, magmatic phenomena, biological processes



Exact origination mechanism may vary depending on the geologic terrain

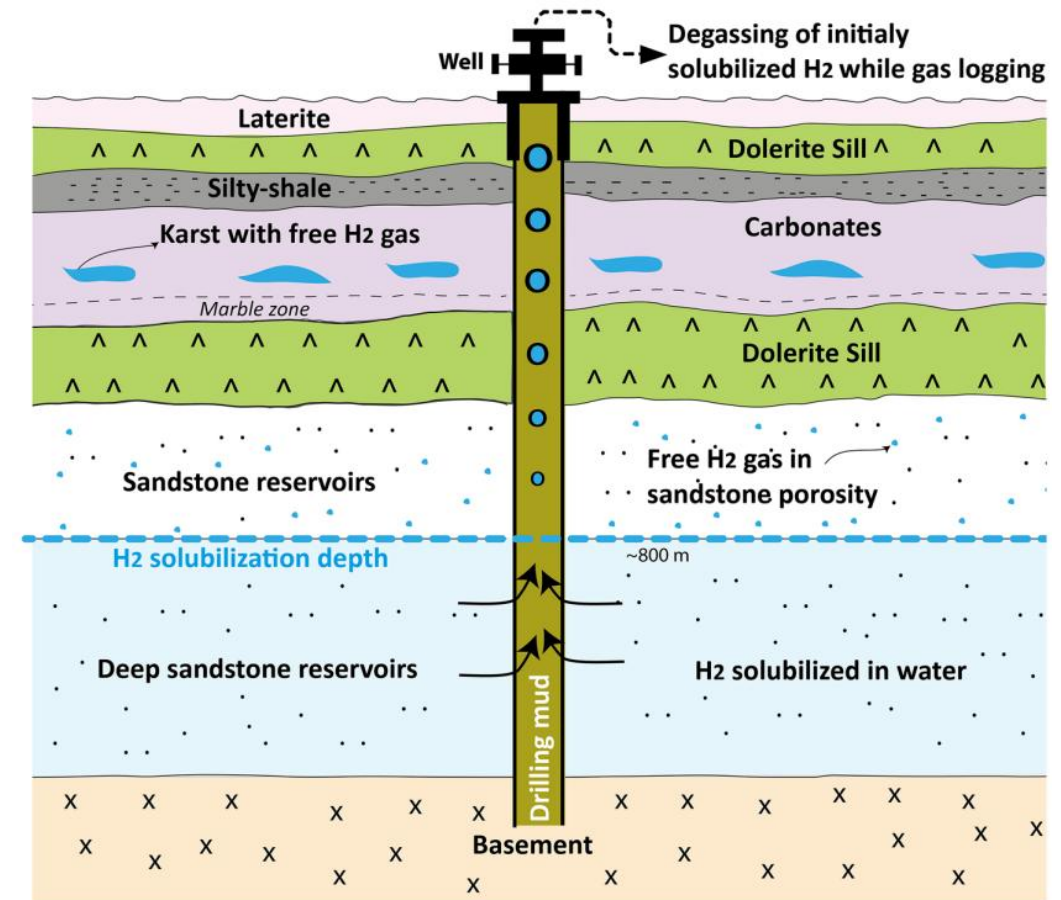
For the large-scale, cost-competitive production, **only options with the highest concentrations that could also be successfully explored/ developed/ commercialised should be pursued**



Can native hydrogen be explored and produced like oil and gas?

- Many anticipate that abundant deposits of native H_2 could be trapped underground in some ways similar to the deposits of natural gas
- This is based largely on the mentioned **assumption** that many of the **potential hydrogen deposits have either been previously overlooked or not searched for**
- These companies are actively applying exploration techniques in the **hope of detecting large concentrations of native H_2 with high purity**
- It is **therefore expected** that native H_2 can then be produced in a way similar to hydrocarbons

The presence of a free gas phase in the uppermost sedimentary reservoirs



Source: Maiga et al (2023)



Companies looking for 'white' and 'gold' hydrogen





Hydrogen as a free gas: Potential for exploration and production using oil and gas technology/ methods

Main factors to consider when identifying if the show is commercially viable:

- **Hydrogen concentrations:**

Low H₂ content is unlikely to make the project economically attractive

- **Well pressure:**

Higher pressure can facilitate easier and more cost-effective extraction, reducing the energy required for compression and boosting the overall efficiency of the production process

- **Production rate:**

The rate at which hydrogen can be produced from the reservoir is a key determinant of commercial viability. Higher production rates lead to lower unit costs due to economies of scale

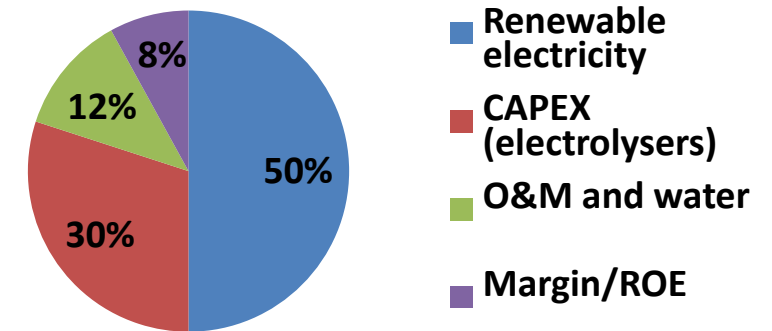
- **Land acreage and mineral rights:**

Large land areas may be required for drilling multiple wells and installing necessary infrastructure

- **Distance to markets:**

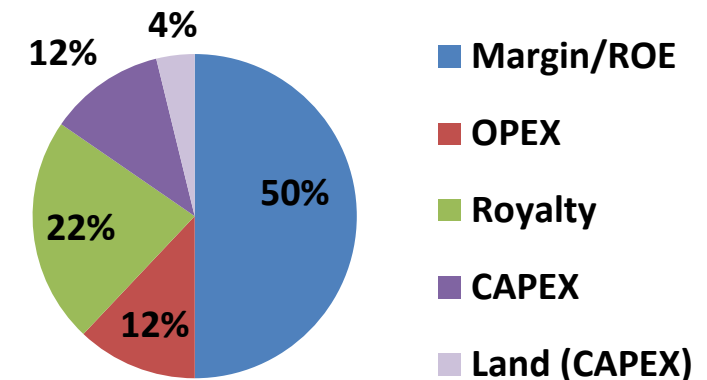
Transportation costs can significantly affect the overall economics of hydrogen projects. Longer distances require more extensive pipeline infrastructure and higher operational costs to transport hydrogen to end-users

Key components of green H₂ production and their respective shares



Source: GEP (2023)

Key components of native H₂ production and their respective shares



Source: Lin and Shuster (2024)



The Bourakébougou field, Mali: The only confirmed native H₂ resource



Characteristics of the project:

H₂ concentration: Up to 98%

Well pressure: ~5 bar

Production rate: Up to 48 t/year

Acreage: 9.8 km

Distance to the capital: 50-60 km

Distance to the nearest port: 1,000 km (Konakry, Guinea)

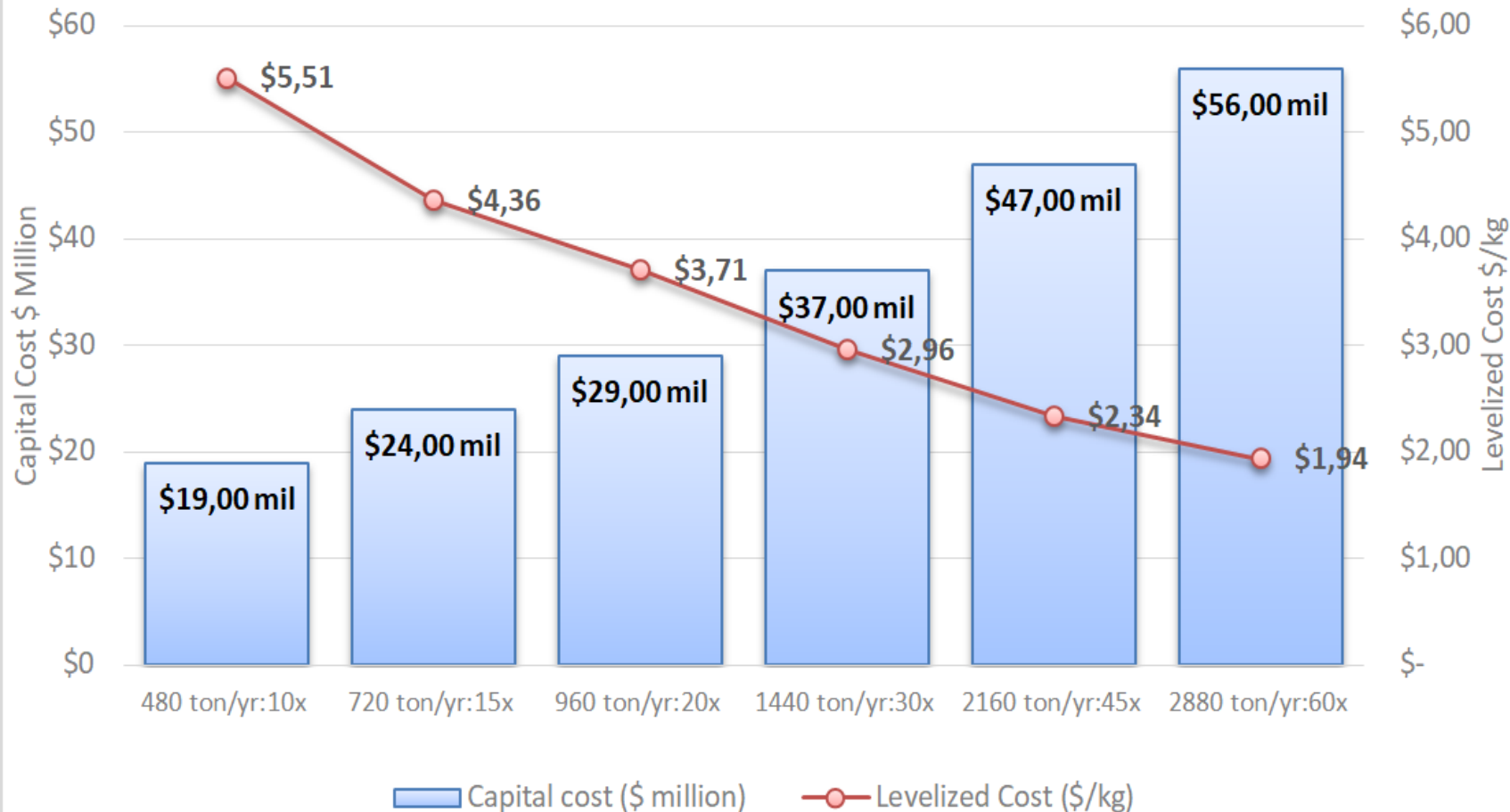


- Despite generating **nearly pure H₂**, the Bourakébougou field can only produce between 5 and 50 tonnes of H₂ per year, which constitutes **the equivalent of 0.3 to 3 barrels of oil per day**
- At such rates, **thousands of wells would be needed to match the output of a relatively small gas field**
- Or at least **10 wells to match the output of an average onshore wind turbine**



What if the Bourakébougou conditions could be replicated at a larger scale?

Capital cost and LCOH by capacity



Source: Lin and Shuster (2024)

- The larger the scale the smaller the LCOH
- A project **10x the size** of that in Mali could potentially generate H₂ **at the cost lower than most green H₂ projects**
- A project **60x the size** of Mali could potentially generate H₂ **at the cost competitive with grey and brown H₂**

The main question is:

Will we find resources similar to but larger than those in Mali?



Why should we even bother?

Key hydrogen generation processes, their estimated carbon intensity and LCOH

Origin	Feedstock/ source	H ₂ production technology/ mechanism		CO ₂ abatement/ elimination technology	Example of main chemical reaction(s)	Estimated carbon intensity (kg-CO ₂ e/kg-H ₂)	Estimated levelised cost of production (USD/kg)
Manufactured	Natural gas	Steam methane reforming		n/a	CH ₄ + H ₂ O → CO + 3H ₂	10.09-17.21	1.03-2.16
				CCS		2.97-9.16	1.22-2.26
		Methane pyrolysis		CCU	CH ₄ → 2H ₂ + C	1.9-9.14	1.36-2.45
	Biomass	Biomass gasification		n/a	C + H ₂ O → CO + H ₂ (steam); C + CO ₂ → 2CO (carbon)	0.31-8.63	1.48-3.00
				CCS		-11.66-17.55	2.27-3.60
		Biomass pyrolysis		CCU	C _x H _y O _z → xC + y/2 H ₂ + CO + CO ₂	TBD	1.21-2.19
	Coal	Coal gasification		n/a	C + H ₂ O → CO + H ₂ (steam); CO + H ₂ O → CO ₂ + H ₂	14.4-30.9	0.96-1.88
				CCS		0.78-10.35	1.40-3.60
	Wind & water	Electrolysis of water	n/a	2H ₂ O → 2H ₂ + O ₂	0.52-2.2	3.56-10.82	
	Solar & water				1.32-7.1	3.34-14.87	
	Nuclear & water				0.47-2.13	3.29-8.21	
	S-I	Thermochemical cycle	CCS or n/a ⁹		0.41-2.2	1.47-2.71	
	Cu-Cl				0.7-1.8	1.47-2.70	
Naturally occurring	Olivine & water	Serpentinisation		n/a	(Mg, Fe) ₂ SiO ₄ (Olivine) + H ₂ O → Mg ₃ Si ₂ O ₅ (OH) ₄ (Serpentine) + Fe ₃ O ₄ (Magnetite)+ H ₂	~0.4-1.5	Potentially <1
	Hydrocarbons/ biomass/ waste & heat	Deep-seated/thermal decomposition		n/a or CCS	CH ₄ → H ₂ + CO		
	Water & ionising radiation	Radiolysis		n/a	2H ₂ O → 2H ₂ + O ₂		
	Organic compound & anaerobic microorganisms	Fermentation	Microbial/ biological		C ₆ H ₁₂ O ₆ → 2CH ₃ COOH + 2H ₂		1.26-10.57
	Photosynthetic bacteria/ cyanobacteria/ algae & light & water	Photosynthesis			2H ₂ O → 2H ₂ + O ₂		

- Companies claim that, in principle, **native hydrogen can be produced at a cost of <1 USD/kg**
- If this is true, it will make it the most cost competitive H₂ production pathway
- It is also expected that the **estimated carbon intensity of native hydrogen is likely to be close to that of green H₂ (or even lower?!)**
- If this is true, native hydrogen may become the cheapest low-carbon H₂ out of all the options

The main question is:

Is it all achievable?



Native hydrogen: Critical unknowns for large-scale production

- We still **don't know specific places where native hydrogen can occur in high concentrations**
- We **don't know if native hydrogen is being generated steadily** (but we assume steady state today)
- Most importantly for **geologic hydrogen resource potential is accumulation processes and this is our critical unknown at the moment**

So, in all the cases, except Mali, we cannot talk about reserves – only potential resource based on occurrences (seeps and vents, etc.)

Reserves are those quantities of hydrogen that are anticipated to be commercially recoverable under defined conditions

Resources are further defined as:

- ***Contingent*** (hydrogen potentially recoverable from known applications but not or not yet commercial)
- ***Undiscovered Hydrogen Initially In Place*** (undiscovered accumulations)
- ***Prospective*** (undiscovered hydrogen but potentially recoverable)
- ***Unrecoverable*** (hydrogen not or not yet recoverable)

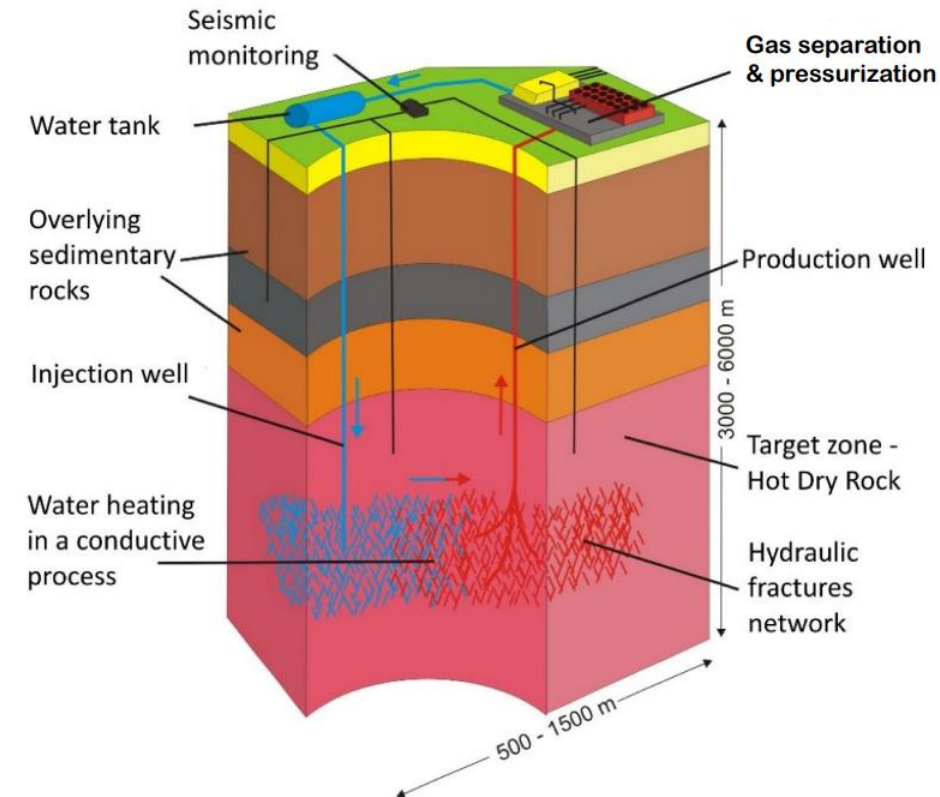


Perhaps we can just stimulate hydrogen production?

Stimulated hydrogen production in the context of native hydrogen refers to methods that enhance the extraction or release of naturally occurring hydrogen from geological sources

- **Hydrothermal methods:** Using high-temperature water to dissolve and release hydrogen from minerals or rocks
- **Geothermal stimulation:** Utilising geothermal energy to heat subsurface rocks, which can promote chemical reactions that release H_2
- **Fracking:** Creating fractures in rock formations to release trapped gases, including hydrogen
- **Microbial/ chemical/ electrochemical stimulation:** Enhancing the activity of hydrogen-producing microbes in subsurface environments/ injecting chemicals/ applying currents that react with hydrogen-bearing minerals to release hydrogen gas
- **Pressure Reduction:** Lowering the pressure in hydrogen-rich geological formations to stimulate the release of hydrogen gas

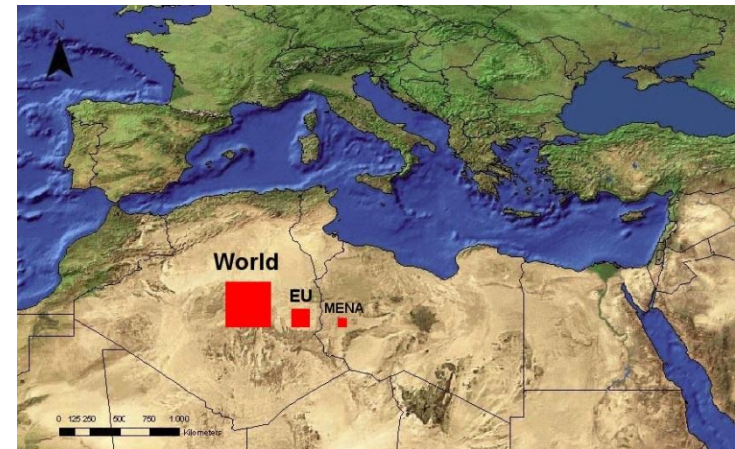
But all still at very low TRL levels (research phase)! Source: Ellis (2023)





General conclusions and food for thought

- **Most naturally occurring hydrogen is likely inaccessible**
- Even most of the hydrogen as a free gas **will most likely be too deep, too far offshore, or/and in accumulations that are too small** (i.e. will not be a commercially viable resource)
- However, even if a **few percent of that hydrogen could be recovered**, it would still be **“enough to supply all projected H₂ demand (~500 Mt/year) for hundreds of years”**
- Most hydrogen occurrences discovered by chance, so **further research is needed** to better understand hydrogen accumulation processes and develop exploration techniques
- Specifically, **we need to further improve:**
 1. Understanding of the hydrogen system
 2. Surface exploration techniques
 3. Subsurface exploration tools
 4. Stimulated hydrogen production



Same ambitions, same challenges?



Thank You!

[\[aliaksei.patonia@oxfordenergy.org\]](mailto:aliaksei.patonia@oxfordenergy.org)

A solid teal horizontal bar with rounded ends at the bottom of the slide.