U.S. DEPARTMENT of ENERGY | Office of Energy Efficiency and Renewable Energy

INCREASE YOUR H2IQ

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Today’s Topic: Geologic Hydrogen

April 24, 2025

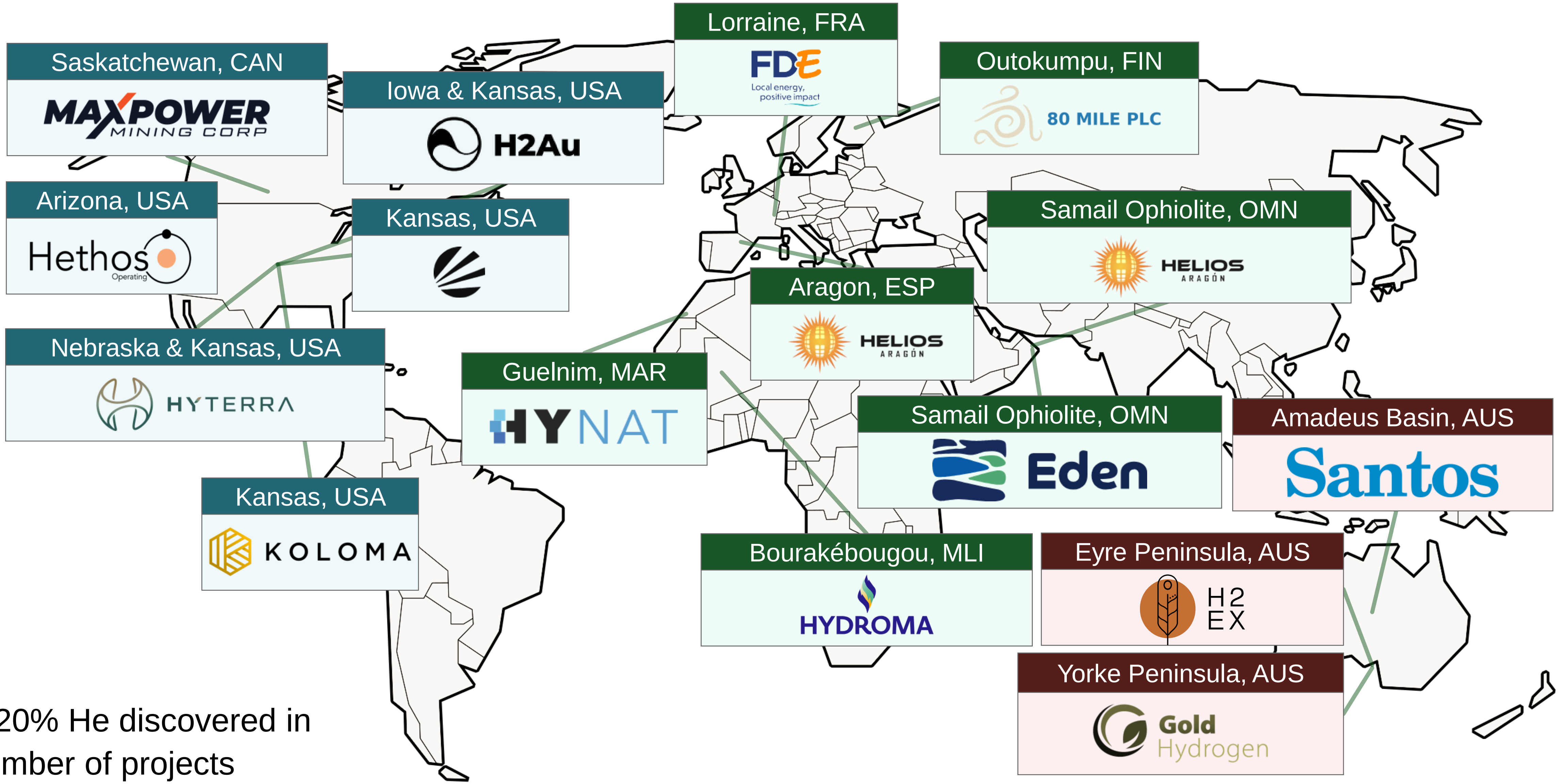
This presentation is part of the monthly H2IQ Hour to highlight hydrogen and fuel cell research, development, and demonstration (RD&D) activities including projects funded by U.S. Department of Energy’s Hydrogen and Fuel Cell Technologies Office (HFTO) within the Office of Energy Efficiency and Renewable Energy (EERE).

Geologic Hydrogen (GeoH$_2$)

A new primary energy source

Dr. Douglas Wicks
Program Director

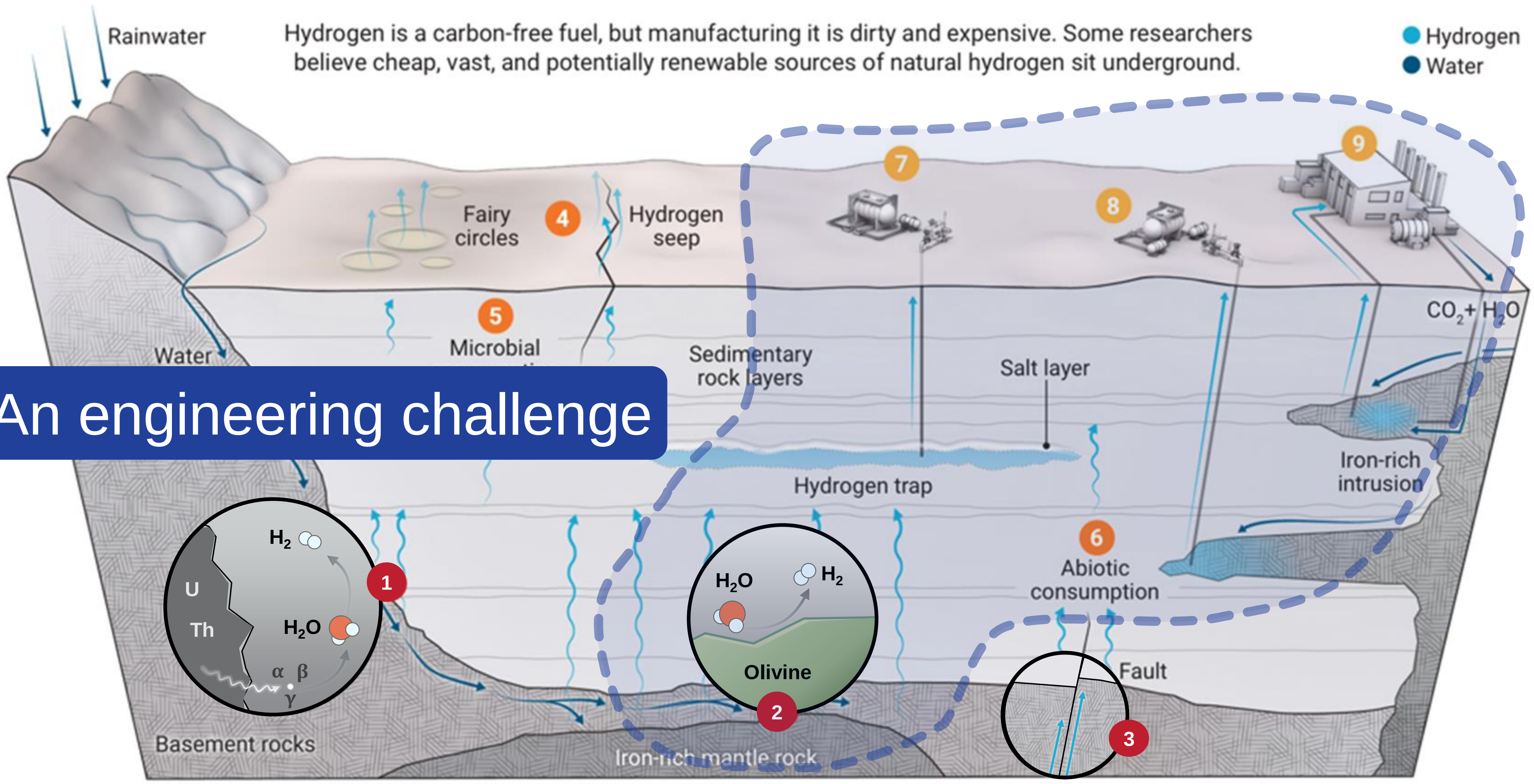
Projects around the world have started development of H_2 wells



3-20% He discovered in number of projects

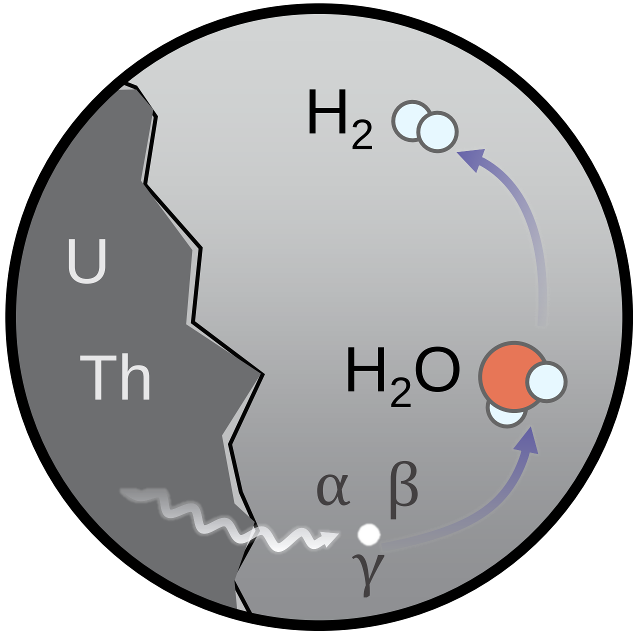
Bloomberg Tech Radar 2024: Geologic Hydrogen Oct 2024

The earth continuously produces subsurface H_2 from geological processes

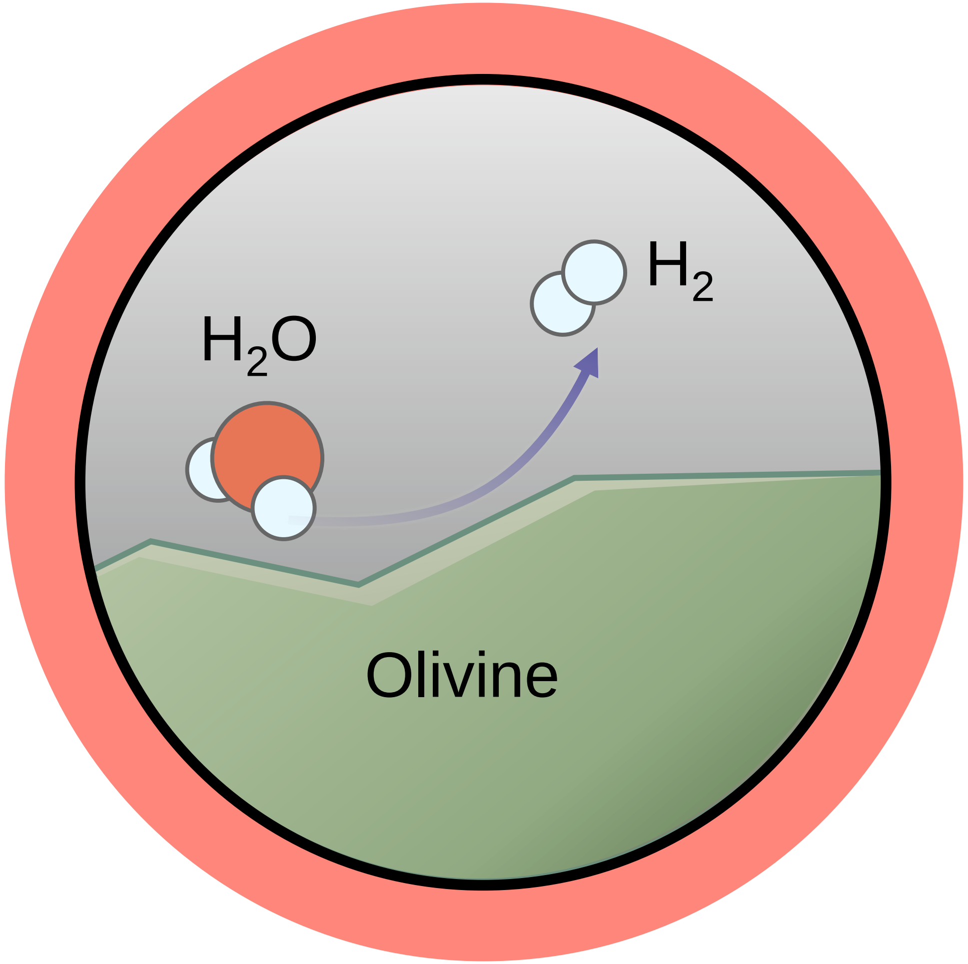


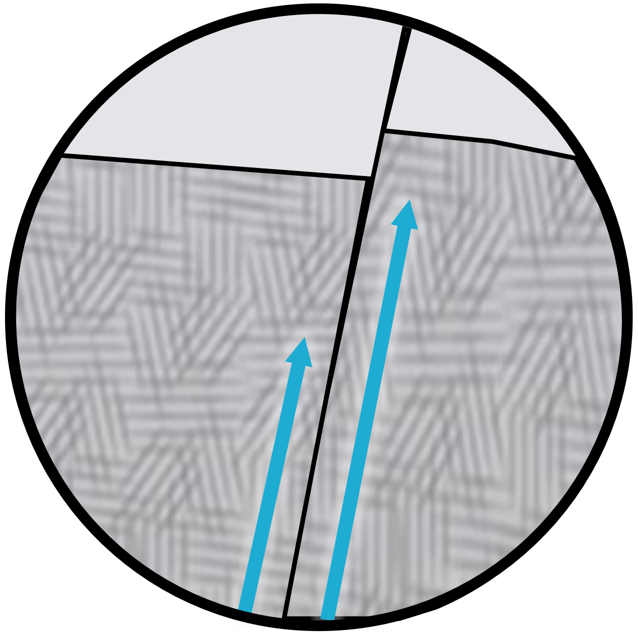
E. Hand, *Science* **379**, 630–636, (https://doi.org/10.1126/science.adh1477) (Feb. 2023).
G. Ellis, S. E. Gelman, *Science Advances* **10,** eado0955, (https://doi.org/10.1126/sciadv.ado0955) (Dec. 2024).

What geologic processes can we control?



❶ Radiolysis of water





❸ "Deep earth" sources

❷ **Iron-based mineral oxidation**

Understanding & controlling reaction conditions necessary for economical GeoH$_2$ production

Serpentinization produces hydrogen

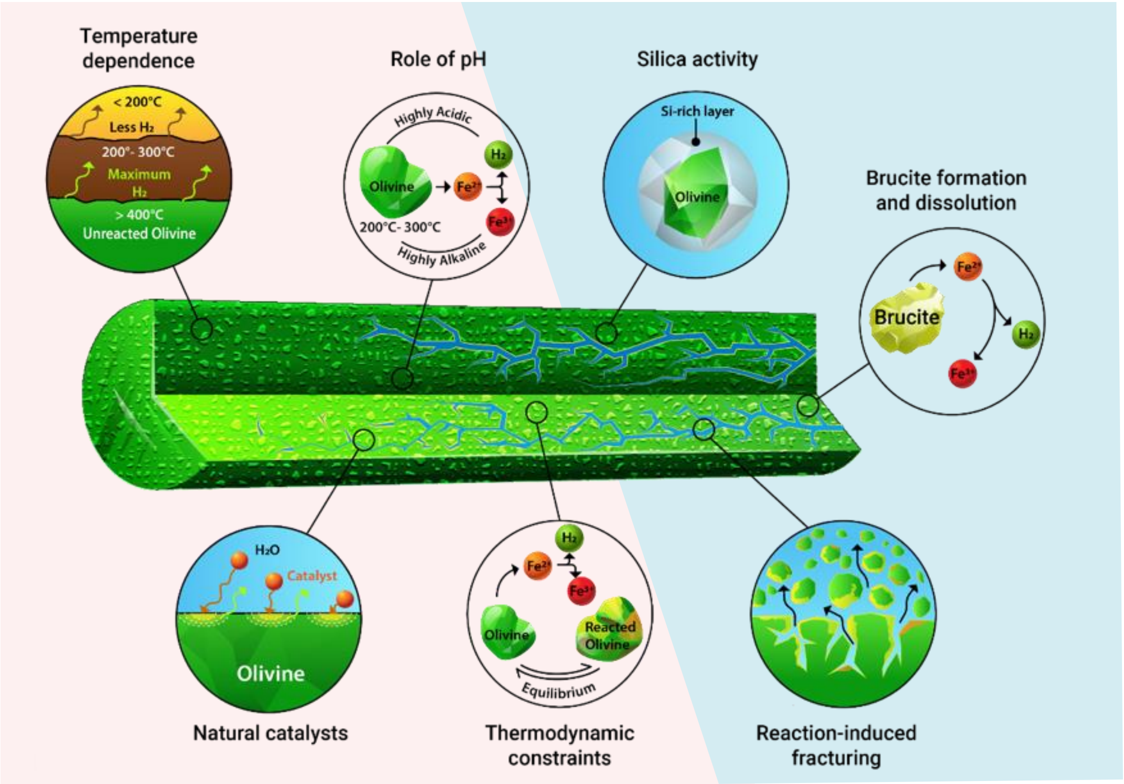
Water | Hydrogen

$$MgFe^{2+}SiO_4 + H_2O \rightarrow (Mg, Fe^{2+})_3Si_2O_5(OH)_4 + (Mg, Fe^{2+})(OH)_2 + Fe^{2+}Fe^{3+}O_4 + H_2$$

Olivine-type rocks | Serpentine | Brucite | Magnetite

Accelerating

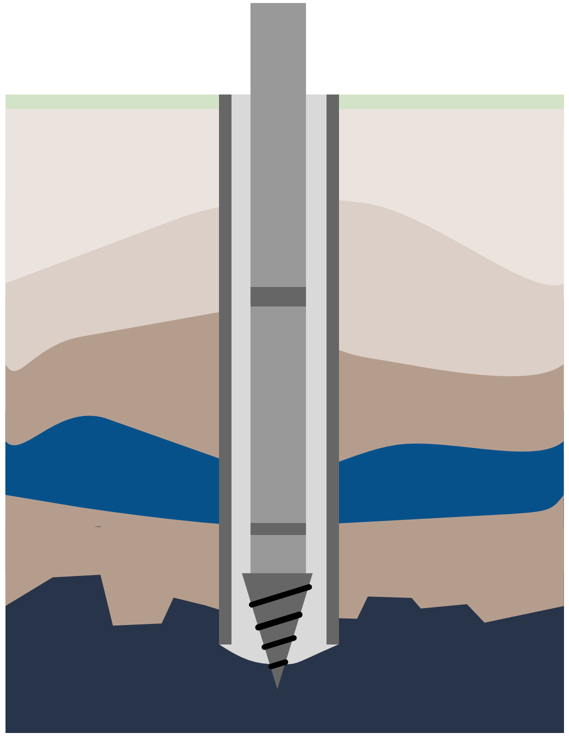
Optimizing hydrogen production requires **understanding and controlling the factors that influence reaction kinetics**



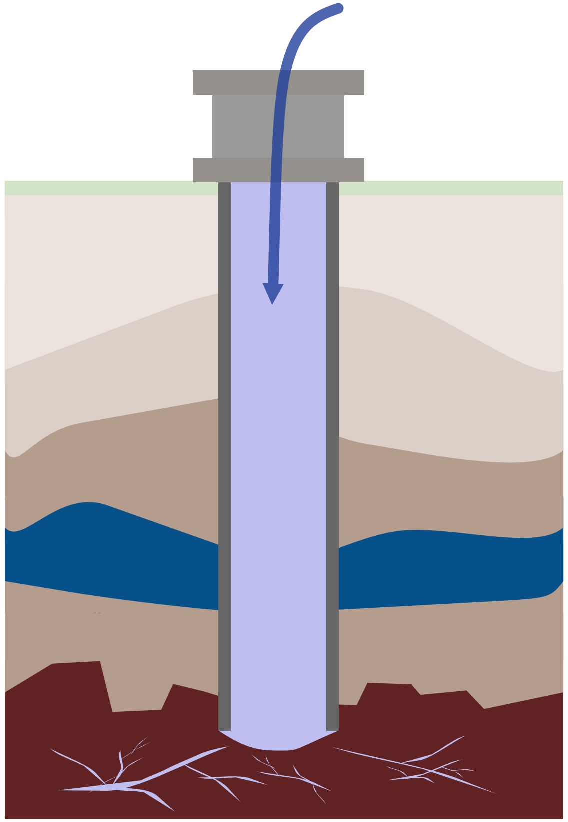
Sustaining

Reaction consumes reactants, finding **methods to increase the available reactive surface and extent of the reaction**

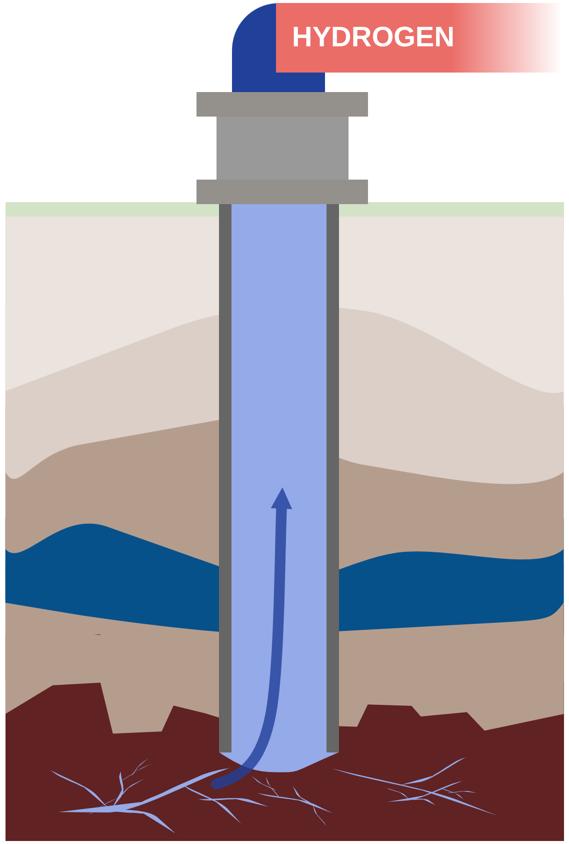
Conceptually: It is an easy problem



Drill a well

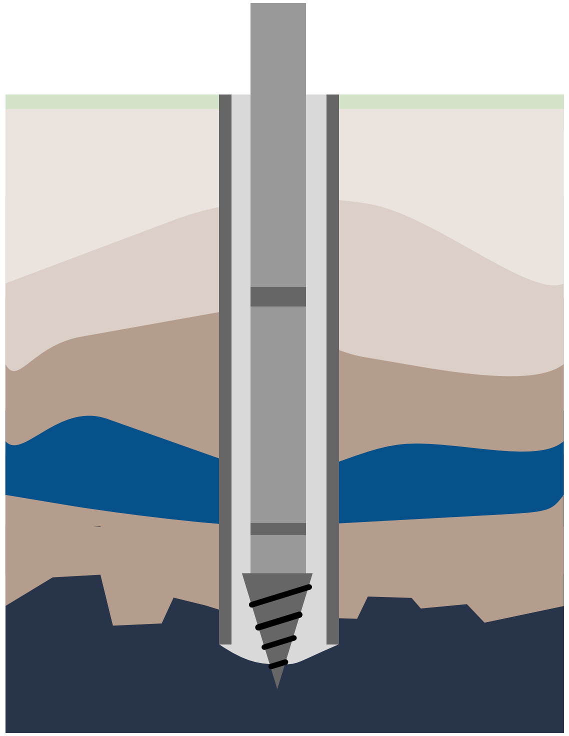


Maybe put something into the well

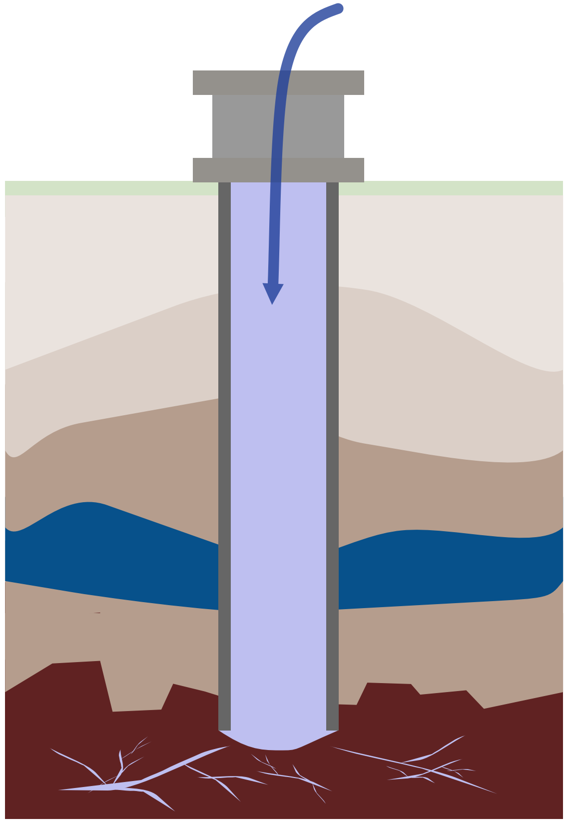


Take H_2 out of the well

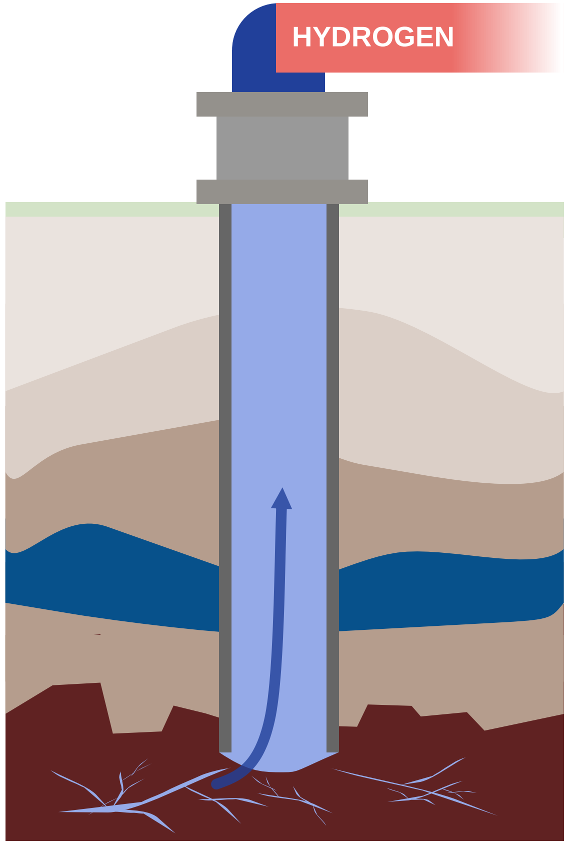
In reality: It is can be a very complex and difficult problem



Where to drill?
What configuration?



What do we put down?
Chemical/Mechanical/Thermal?



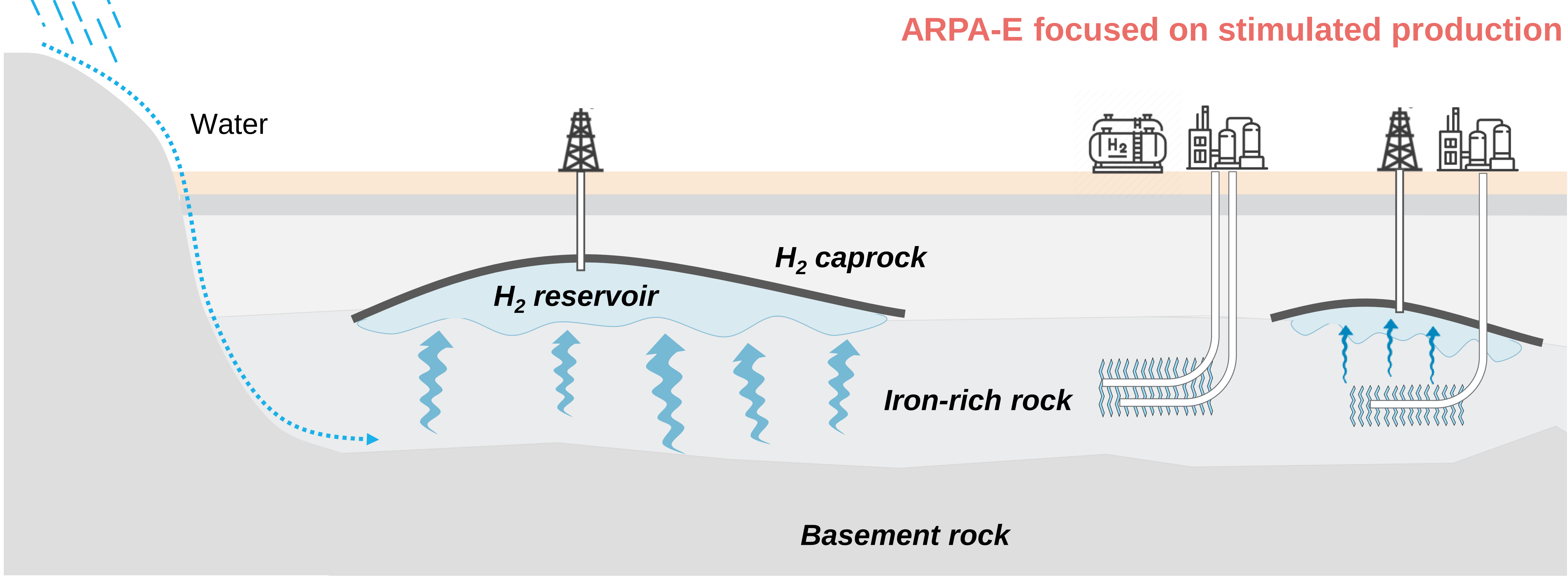
H_2 separation?
Produced water?

Extract natural H_2, or stimulate production using the Earth as a reactor

Natural hydrogen extraction targets existing reserves of subsurface hydrogen that have migrated through the subsurface and been trapped under a caprock, like natural gas

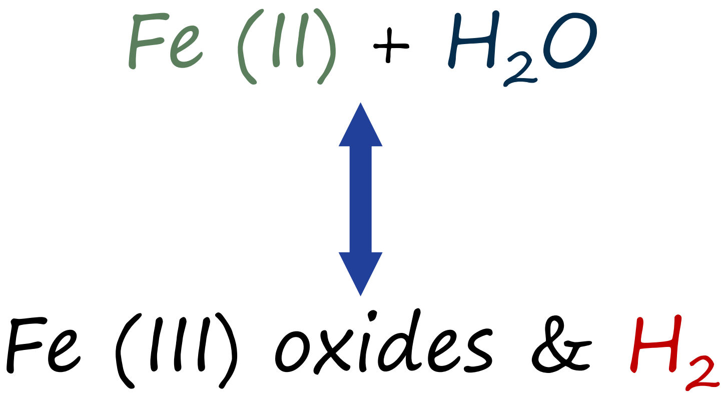
Stimulated production injects fluid into iron rich-rock, causing hydrogen-generating reactions, this hydrogen is collected and returned to the surface, like enhanced geothermal

ARPA-E focused on stimulated production



Understanding the reaction

- Can the oxidation of Fe(II) to Fe(III) be catalyzed in situ?
- This is an equilibrium reaction
  - How important is the equilibrium?
  - Can it be shifted?
  - (note – at pressure the equilibrium $[H_2]_{aq}$ is below solubility)
- What is the impact of mineralogy?
  - Impact of trace elements? Microstructure?
- Are there other H_2 forming reactions to be developed?



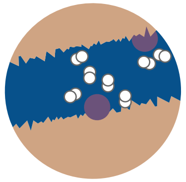
ARPAE

ARPA-E GeoH$_2$ Program

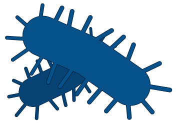
Stimulation and Engineering

Program goals: Answering the major questions needed to unlock GeoH_2

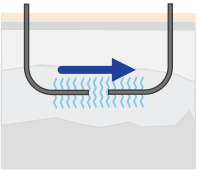
How much surface area is needed to sustain H_2 production? What are methods to increase reaction surface area?



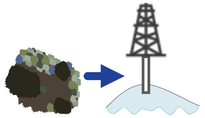
What mineralogy is best at catalyzing H_2 production? What kind of chemical environment or conditions are needed for optimal production?



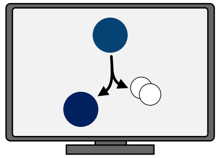
What kind of microbes consume H_2 and can how does suppressing them effect production?



Can we use existing oil and gas or geothermal technologies to extract produced H_2, or will we need to invent new methods?



What can experiments done on rocks and cores tell us about potential risks and reservoir conditions over time?



What models and/or monitoring techniques can support the development of geologic H_2 technologies?

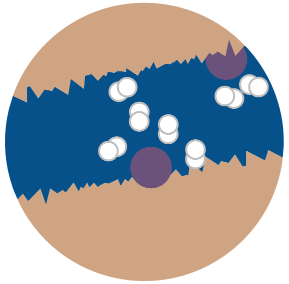
Project overview (Stimulation)

Surface area

Self propagating fracture networks

Electric reservoir stimulation via fracturing

CO_2-based fracturing and reservoir creation

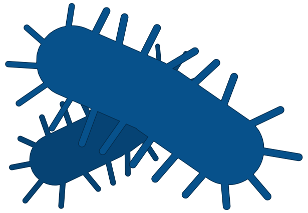


Catalysts

Accelerated mineral and reaction conditions parameter study

Ligands and silicate chemistry effect

Mineral-hosted catalysts in Midcontinent Rift rocks

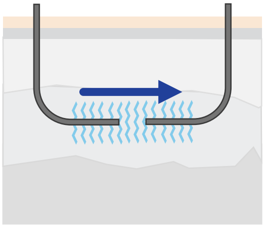


Microbiology

Geochemical and microbial models in different rock systems

Metal ion catalysts with biological stimulation methods

Project overview (Engineering and Support)

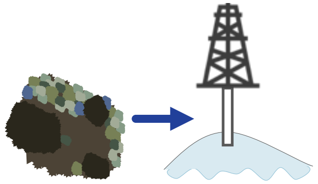


Production and extraction

Cyclic fluid injection and seismicity risk

Foams for higher efficiency H_2 extraction

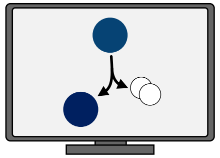
Industrial oil and gas applied to geologic H_2 systems



Rock-to-reservoir characterization

Reservoir management and risk mitigation

Laboratory experiments and simulations for reservoir conditions



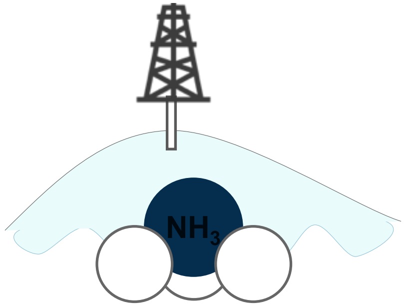
Modeling and monitoring

Economical geophysical characterization methods

Mineralogy and reaction conditions modeling for projects

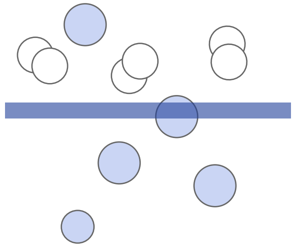
Develop a life cycle analysis via the GREET model

ARPA-E additional selected high risk GeoH_2 projects through VISION OPEN 2024



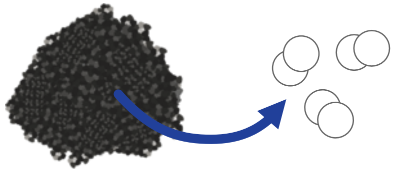
ADDIS ENERGY

Geologic ammonia from wastewater



OSMOSES

Geologic H_2 powering He separation



Fortescue

Processing iron ore tailings for H_2 production and waste iron ore valorization

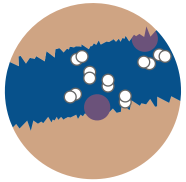
These projects have been selected for award negotiations and have not yet been awarded.

ARPA-E GeoH$_2$ Program

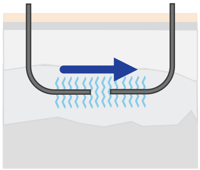
Tantalizing Results

Program progress: Answers are coming in

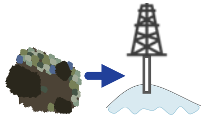
Impact of surface area and depth of reaction work coming together. A number of different rock cracking approaches yielding results – more to come



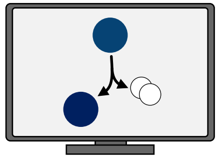
HUGE impact of ore composition/mineralogy seen. Good progress on identifying catalysts and impact of reaction conditions.



Ability to partition hydrogen gas out of aqueous phase at high pressure demonstrated! Several other separation methods in development



What can experiments done on rocks and cores tell us about potential risks and reservoir conditions over time?



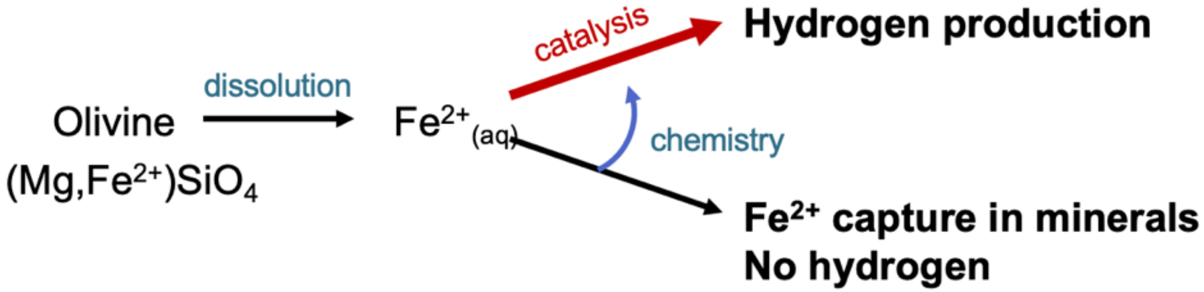
What models and/or monitoring techniques can support the development of geologic H_2 technologies?

Addis Energy | Spin off from MIT GeoH$_2$ project and selected for VISION OPEN 2024

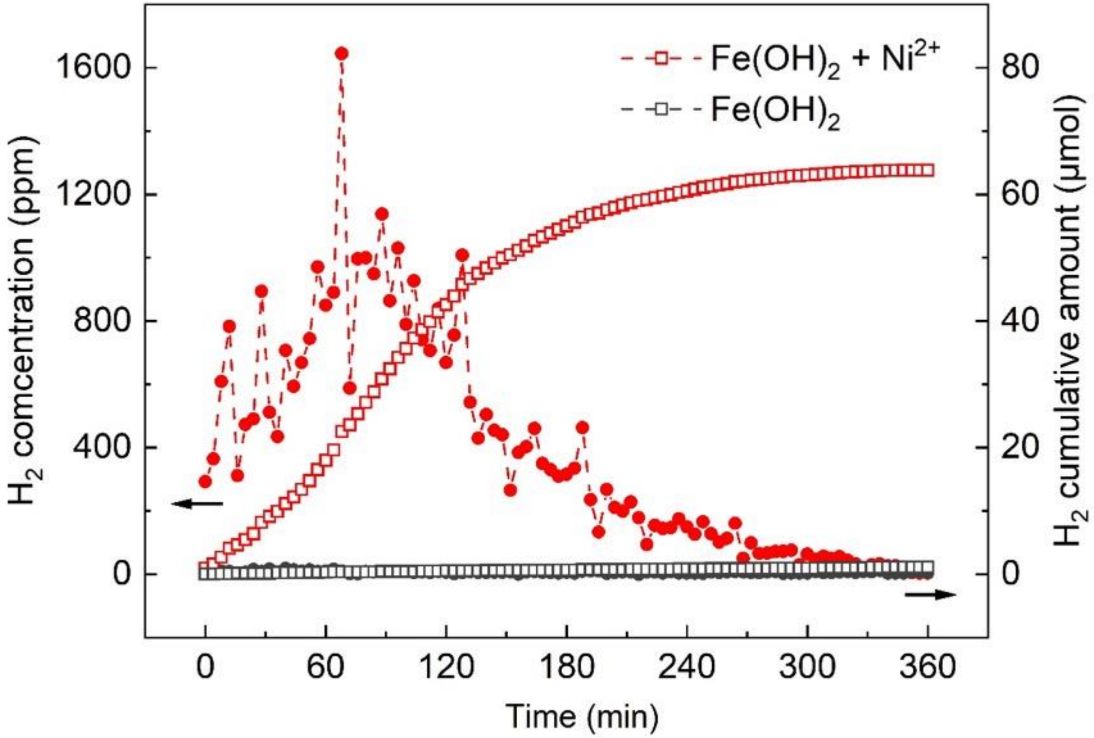
- Focuses on NH_3 production in subsurface
- **H_2 component comes from iron oxidation**
- **Injection of N source with additives into Fe containing ultramafic ores**
  - Low T/P formation possible when N source is a nitrate
  - N_2 gas can be converted at high T with concurrent geothermal energy recovery
- Estimated cost of production ~$200 per tonne of NH_3

Y. Gao, et al., *Joule*, 101805, (https://doi.org/10.1016/j.joule.2024.12.006) (Jan. 2025)

MIT | Catalysis of the oxidation reaction



1 atm | 90°C



ARPA-E GeoH$_2$ Program

Technoeconomic Modeling

TEA follows the stages of well development: early exploration to production

DOE Data Sources

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
GEOTHERMAL TECHNOLOGIES OFFICE

INL Idaho National Laboratory

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Sandia National Laboratories

ARPA-E Model

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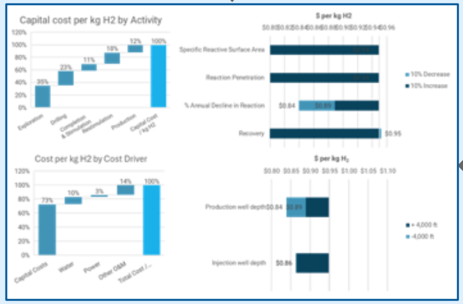
Geologic Hydrogen Exploration & Extraction
Techno-Econmic Analysis
9/13/2024
Author: Bennett Johnson



Industry Experts & Reports

FERVO ENERGY

slb

eia

HYTERRA

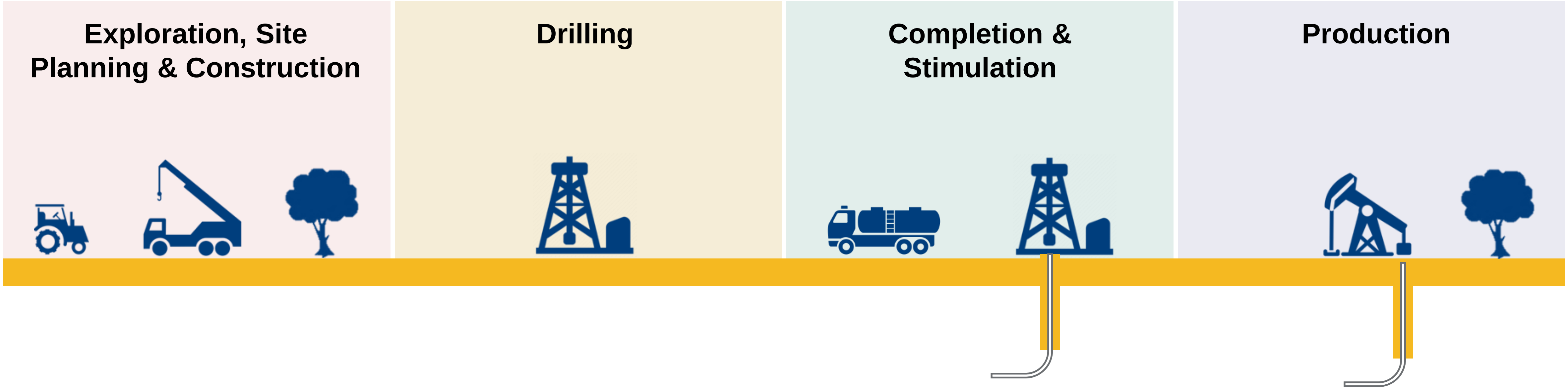
Xcalibur SMART MAPPING

ENVERUS

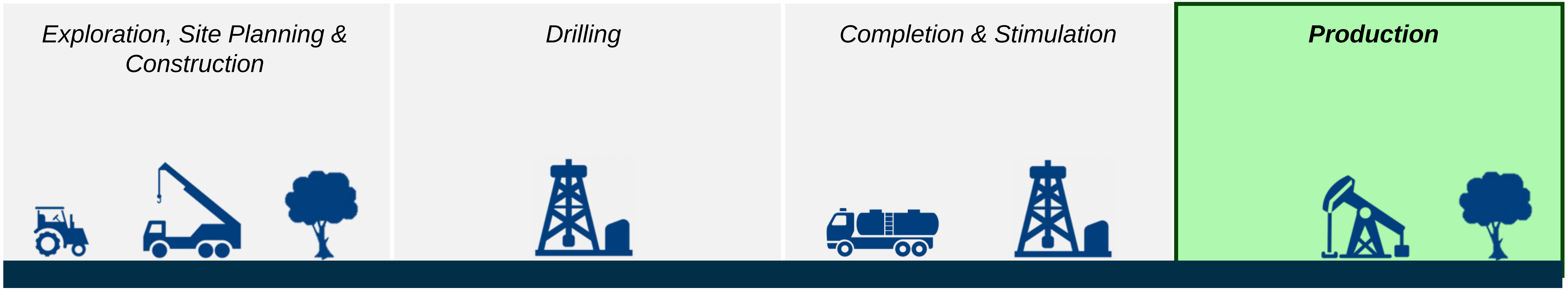
Wood Mackenzie

HALLIBURTON

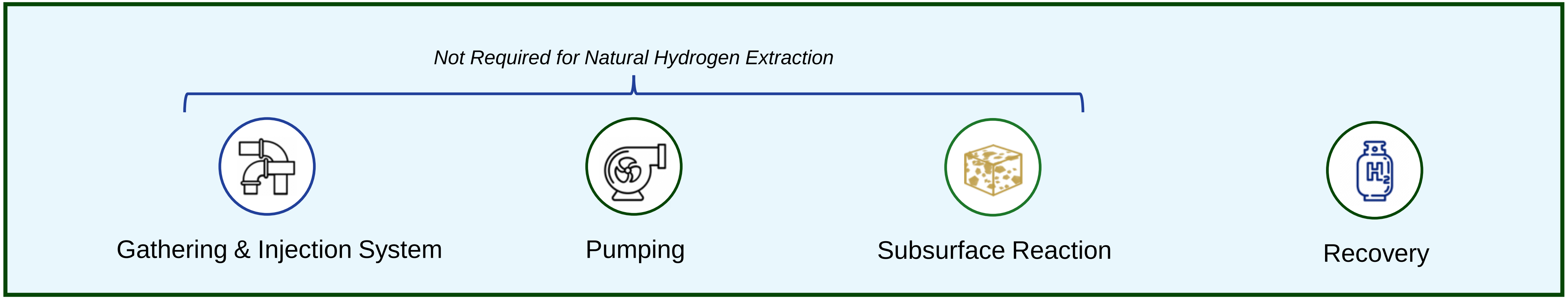
TEA follows the stages of well development: early exploration to production



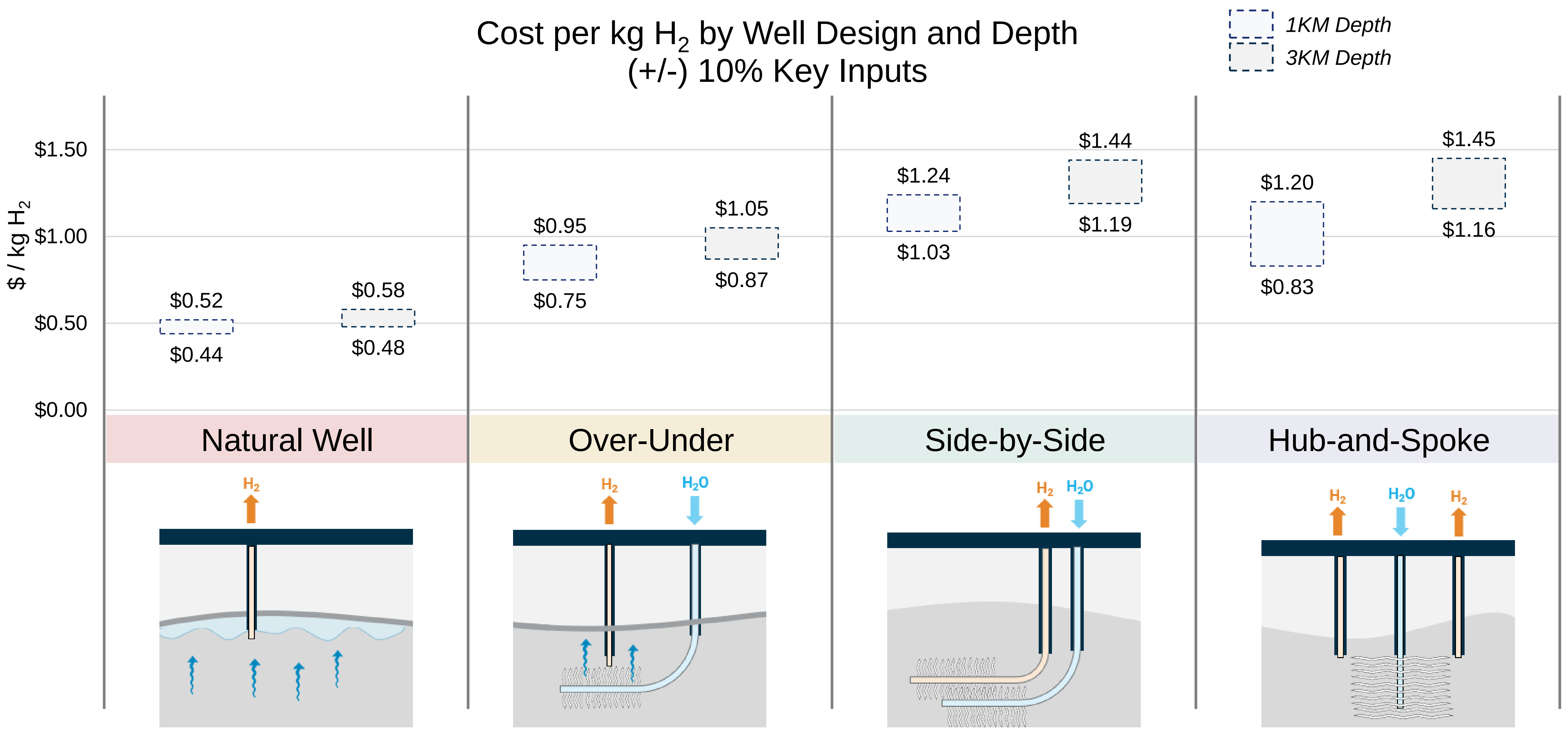
Key activities in Production



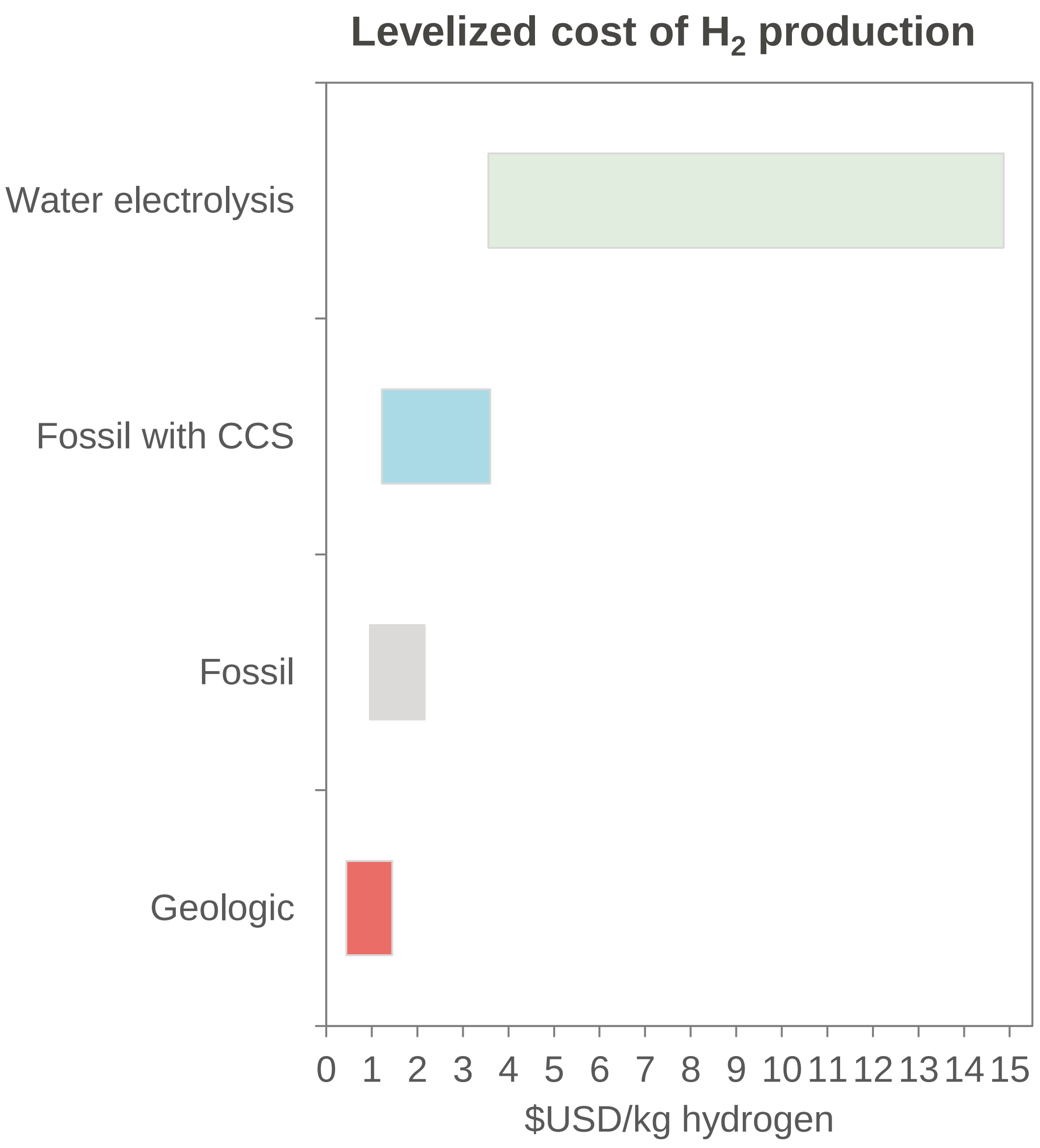
Production Process

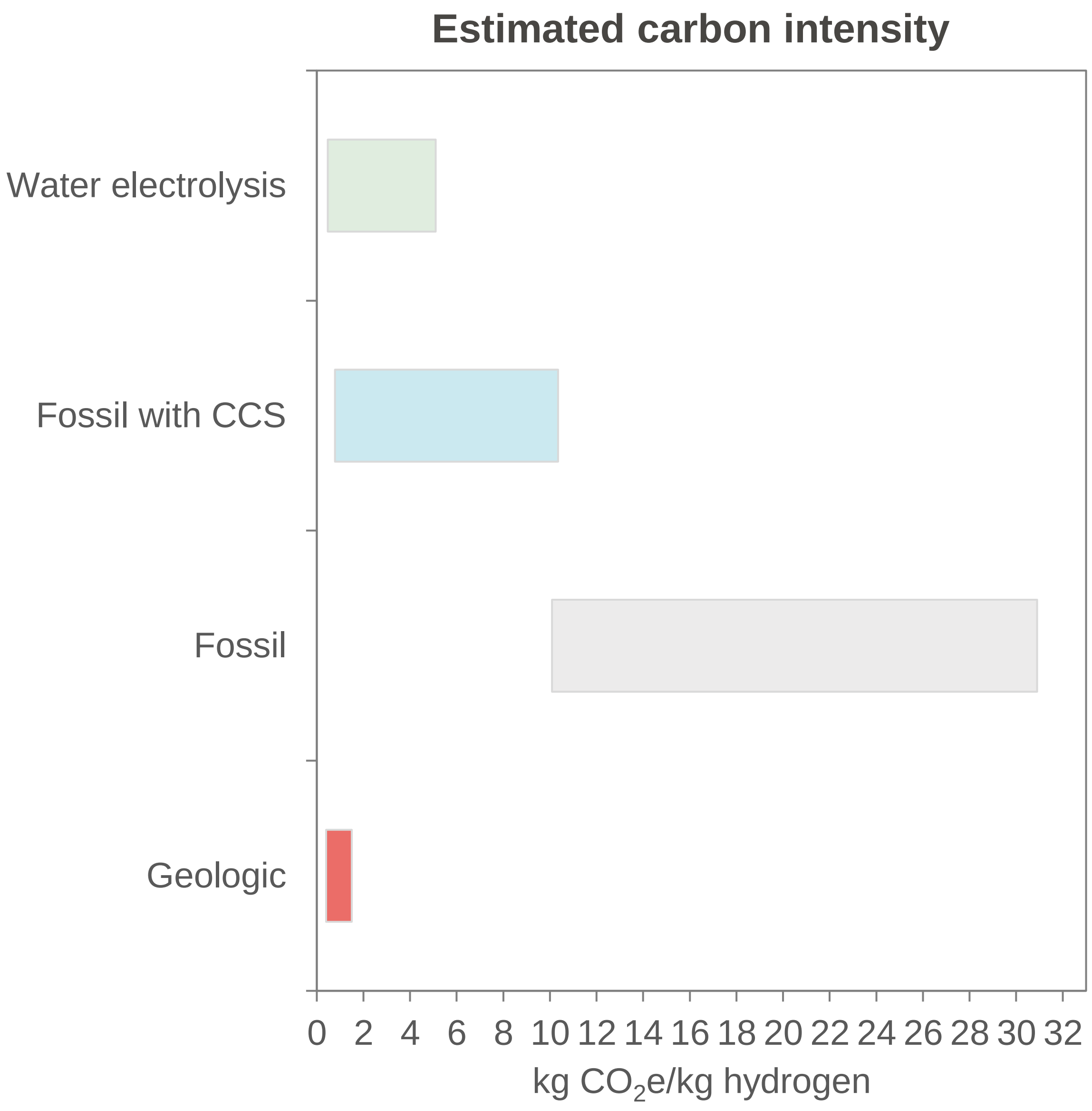


Preliminary Results of TEA



$GeoH_2$ is potentially the cheapest & cleanest form of H_2 production





*Geologic H_2 estimates are based on ARPA-E analysis, project input, and source cited below
A. Patonia, M. Lambert, N. Lin, M. Shuster, The Oxford Institute for Energy Studies (2024)

The Future

Photo credit: Alexis Templeton

Natural Hydrogen: An Overlooked Potential Energy Resource

Geoffrey Ellis

Research Geologist

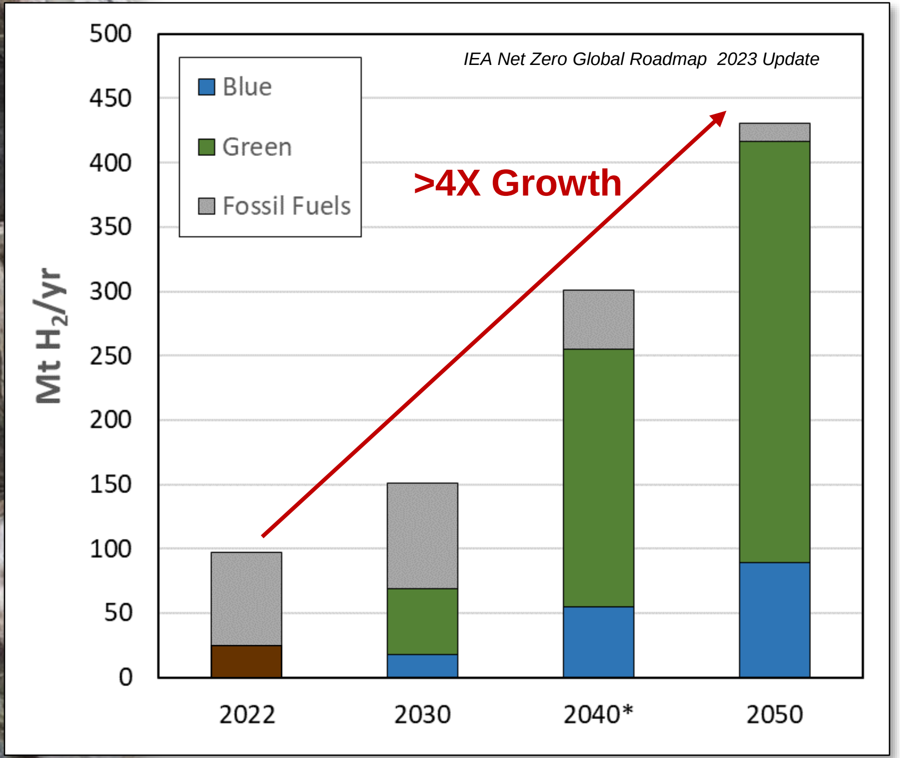
U.S. Geological Survey

USGS science for a changing world

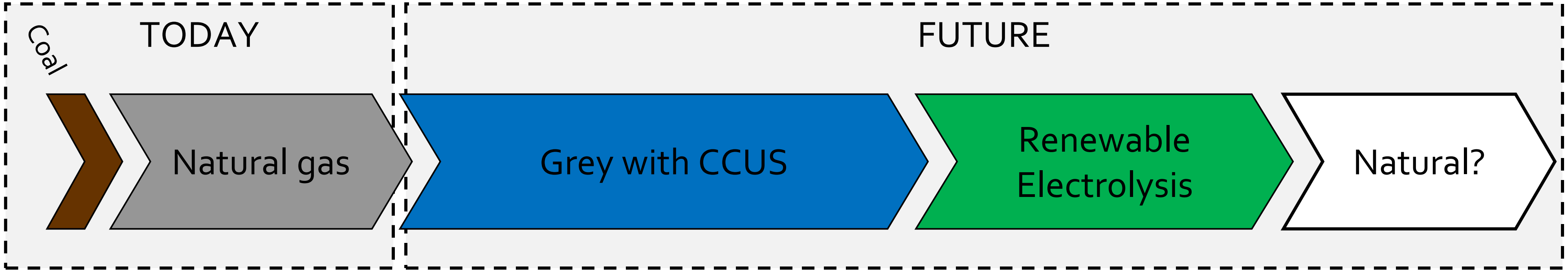
Department of Energy H_2IQ Webinar, April 24, 2025

DEPARTMENT OF ENERGY UNITED STATES OF AMERICA

Global hydrogen supply today & tomorrow



- *Today* – petroleum upgrading, fertilizer, petrochemicals
- *Future* – energy for hard-to-abate sectors — aviation, steel manufacturing, industrial heating, mining
- Meeting this demand with blue and green hydrogen is likely to be expensive and mineral intensive
- Hydrogen is viewed exclusively as a medium for energy storage and transport **not a primary energy resource**
- What is the resource potential of natural hydrogen?



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Observations of natural hydrogen on Earth

Air

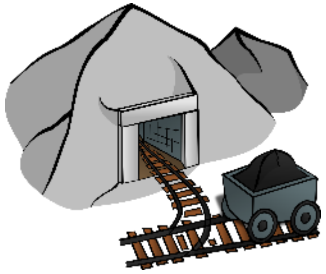
0.5 ppmv

Oceans

Super-saturated

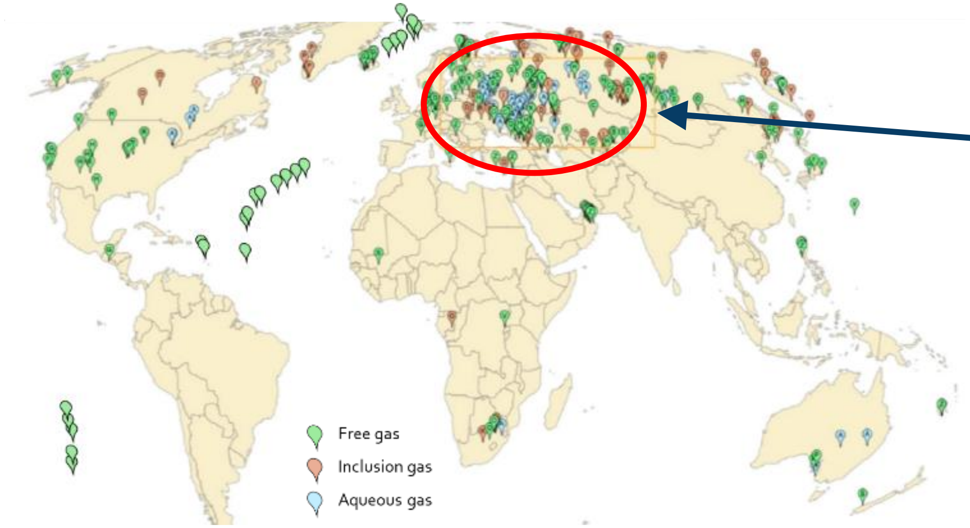
10-1000s ppmv

Deep mines & boreholes



% Concentrations

Surface observations of hydrogen concentrations >10%



Modified from Zgonnik, 2020 and Prinzhofer & Deville, 2015

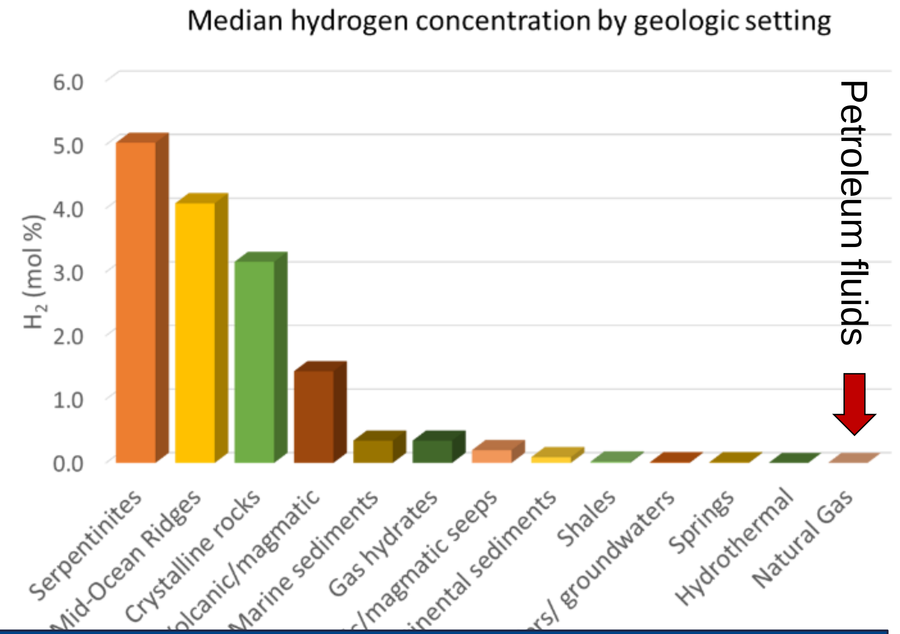
Active research efforts in this region

The more we look for hydrogen the more we find it

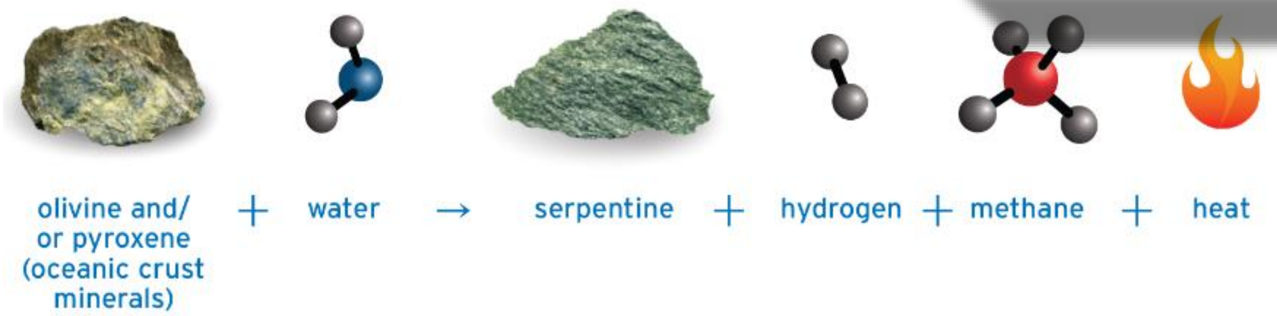
USGS science for a changing world

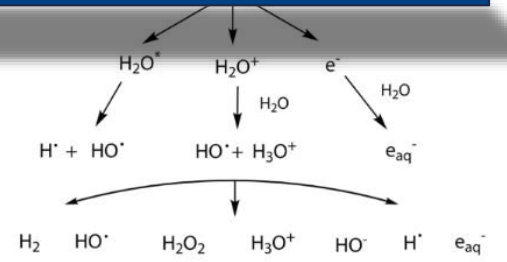
Observations of natural hydrogen on Earth

- More than 30 distinct generation mechanisms
- Reaction of water with ultrabasic rocks (i.e., serpentinization)
- Natural radiolysis of water
- Deep-sources of hydrogen (primordial or generated in the lower crust)
- Other mechanisms
  - High thermal stress of organic matter
  - Mechanoradical reduction of water



High diffusivity and reactivity of hydrogen *probably* means that accumulations cannot form

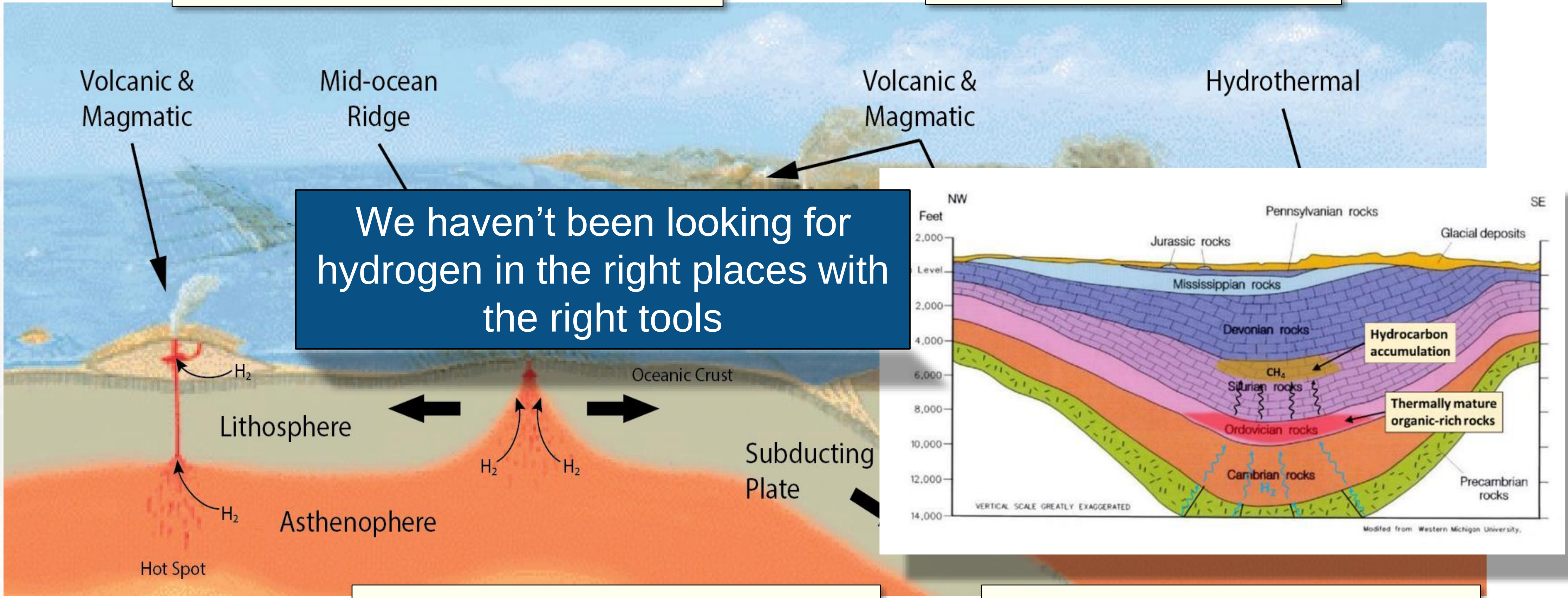




Rethinking geologic hydrogen accumulation potential

Hydrogen generation is generally not where oil and gas is found

Petroleum exploration is not targeted at hydrogen



We haven't been looking for hydrogen in the right places with the right tools

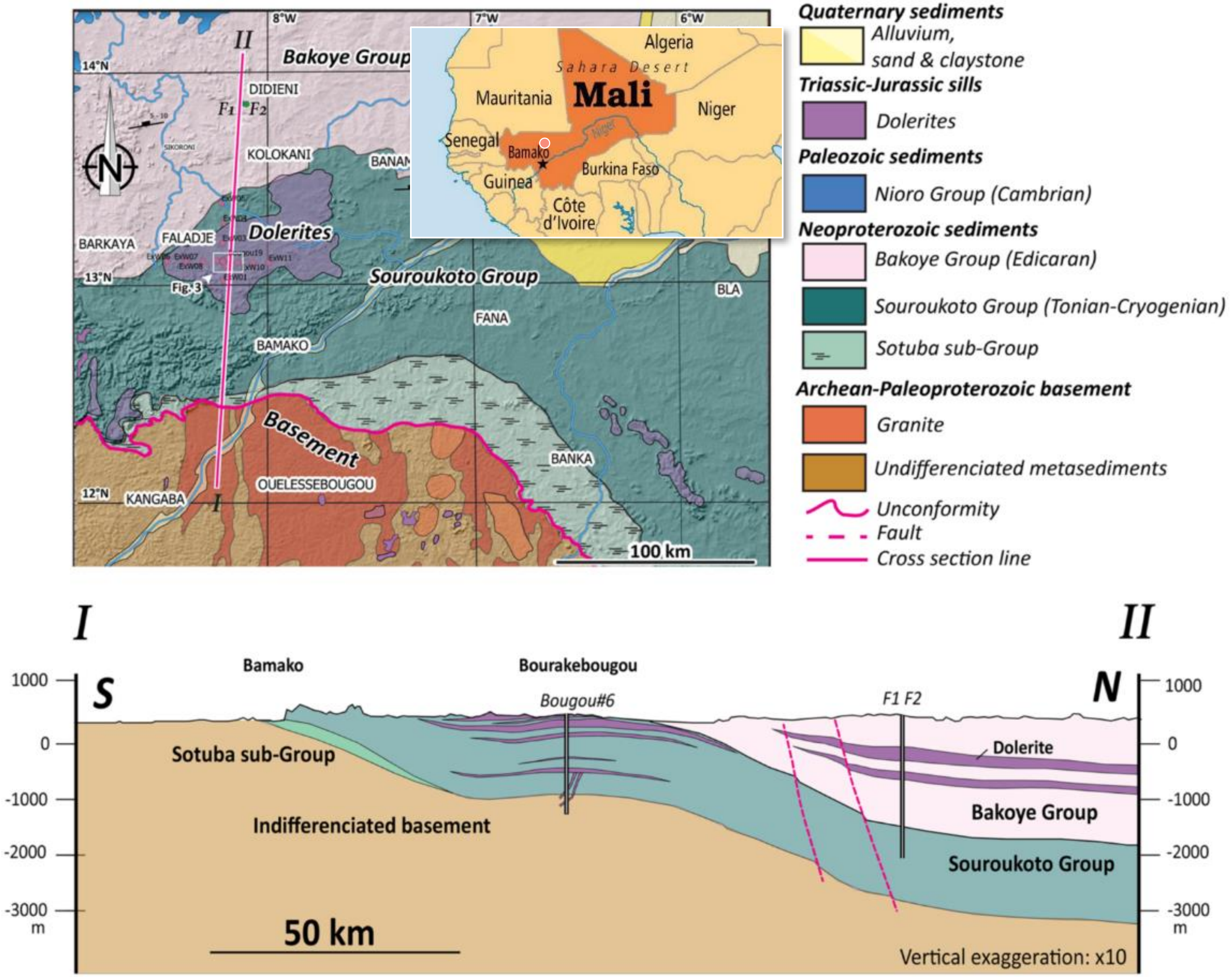
Mineral exploration generally does not look at gas composition

Hydrogen is consumed by hydrocarbon forming reactions

USGS science for a changing world

Hydrogen discovery and production in Mali

- Accidental gas explosion during water well drilling in 1987
- Reoccupied as a gas well in 2012 and produced **>97 % H_2**
- Exploration campaign including seismic, gravity, magnetic surveys and coring
- Multiple stacked carbonate and siliciclastic reservoirs interbedded with doleritic seals
- The **discovery well is still producing**, with the gas generating electricity
- Source of H_2 is not known



(Maiga et al., 2023)

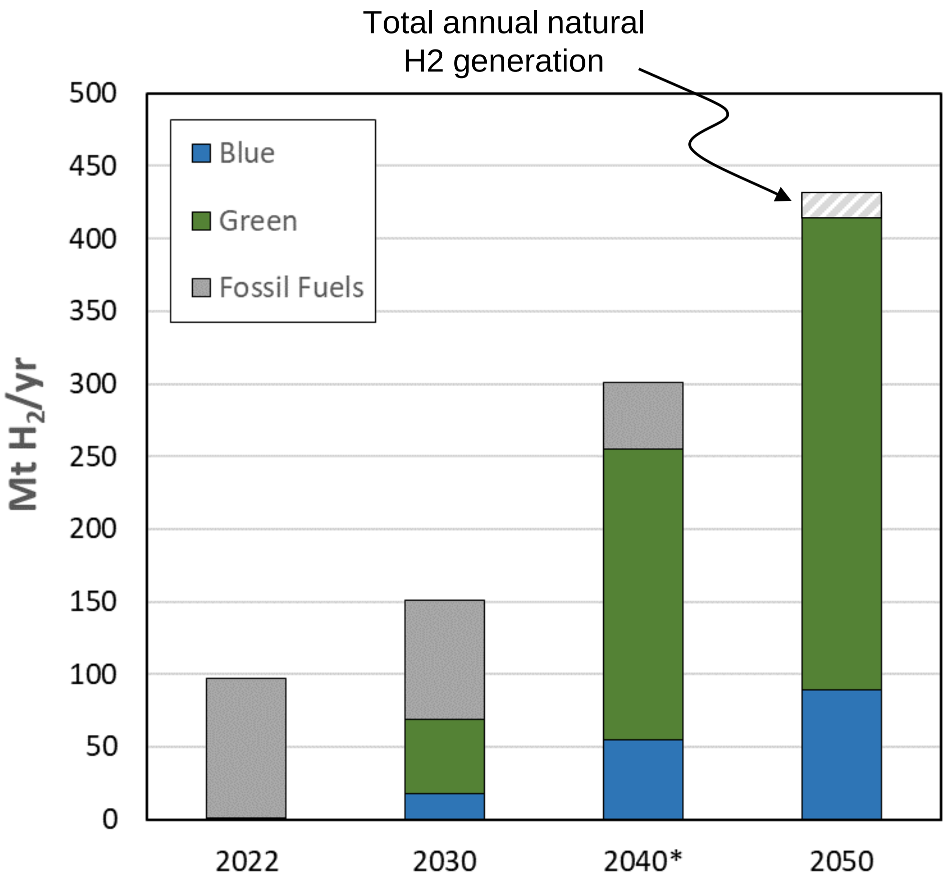
What could the global hydrogen resource potential be?

Context

- Annual global demand projected to be **~430 Mt/yr** by 2050
- Annual global production of natural hydrogen in the subsurface estimated to be **~23 Mt/yr** (*Zgonnik 2020*)
- If we could find and produce all of this, it would only meet **~5%** of global demand

Resource potential depends on:

- Trapping efficiency
- Residence time
- Hydrogen consumption (biotic & abiotic)
- Exploration/production success



IEA Net Zero Global Roadmap 2023 Update

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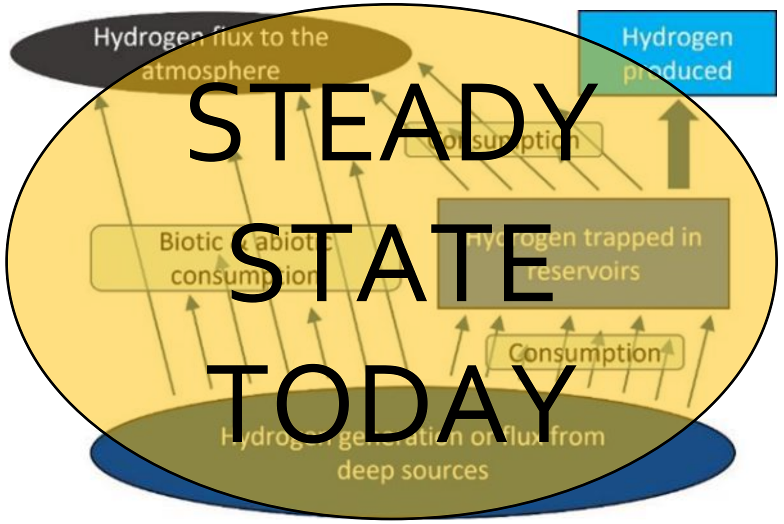
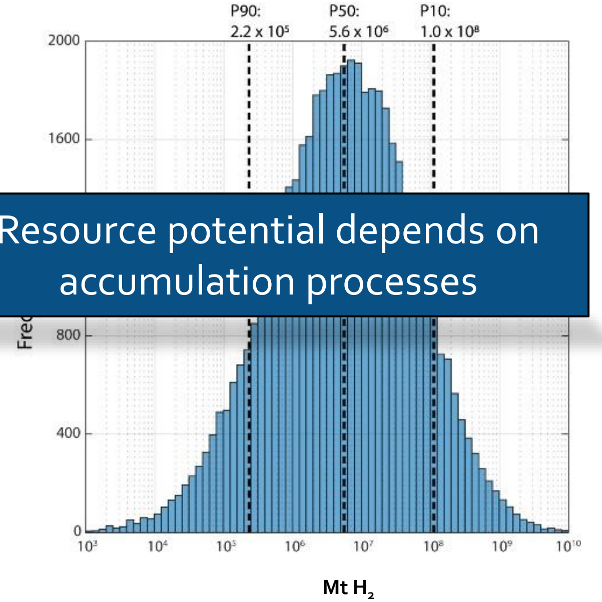
Geologic hydrogen resource model

- Box model for global hydrogen resources
- Inputs constrained by known hydrogen behavior (e.g., estimated annual production, etc.) and analogues (e.g., petroleum, helium, etc.)
- Assume steady state today
- In-place hydrogen amounts may range from thousands to billions of Mt with median prediction of **~5 million of Mt**
- Most hydrogen is likely **inaccessible** – too deep, too far offshore, too small accumulations
- A **few percent** recovery would still supply **all projected H_2** demand (>400 Mt/yr) for 100's of years



Ellis & Gelman, 2024



Resource potential depends on accumulation processes

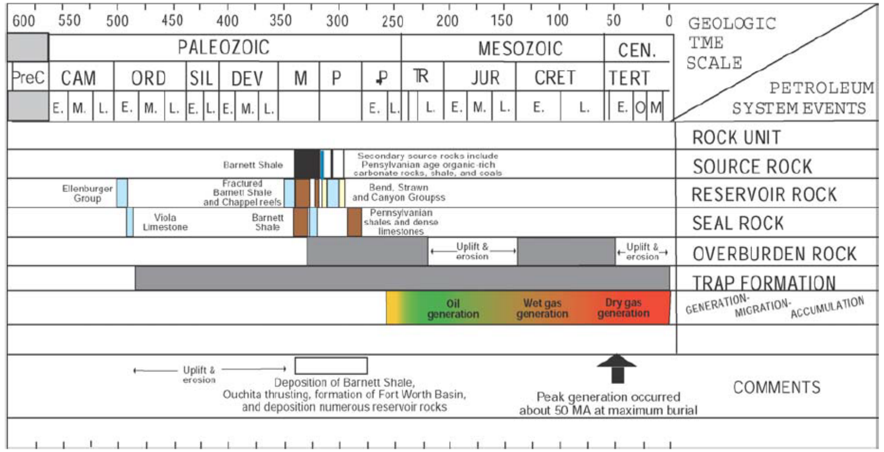
Hydrogen system analogous to the petroleum system

Petroleum System	Hydrogen System
Critical elements	*Essential components*
Source	Source
Migration pathway	Migration pathway
Reservoir	Reservoir
Trap/seal	Trap/seal
Preservation	Preservation
Timing	Timing

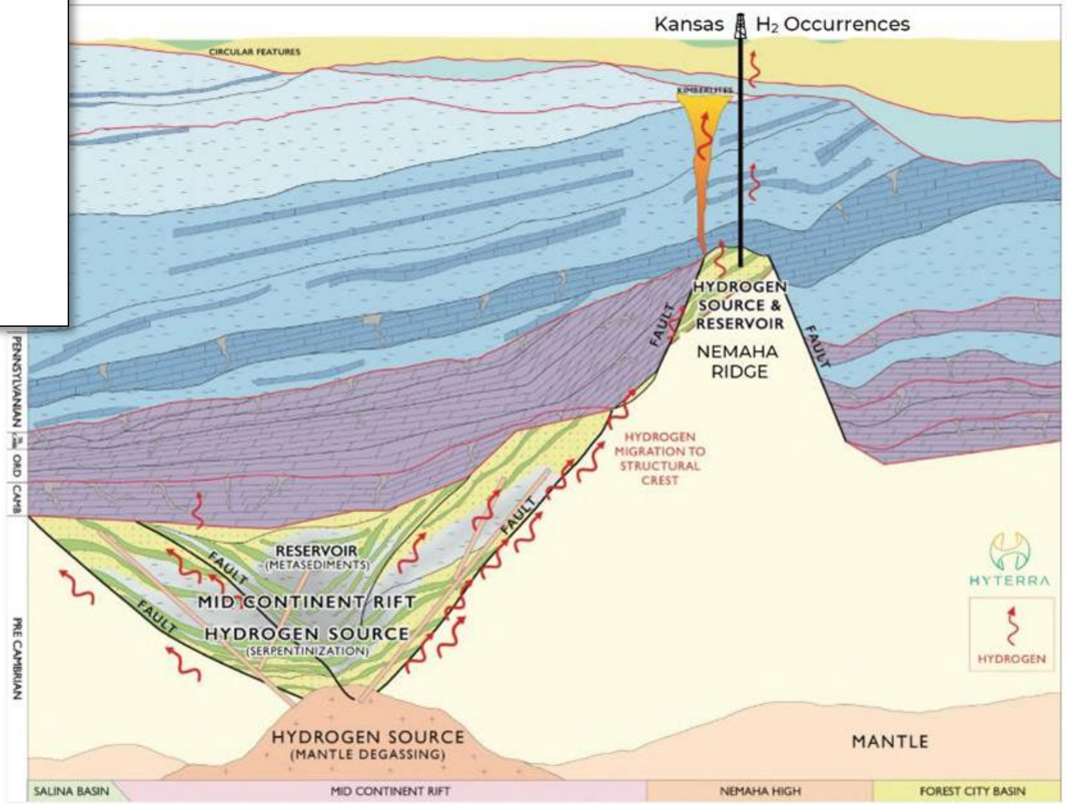
Not completely analogous

Need to adapt for hydrogen

Petroleum system events chart



(Pollastro et al., 2003)



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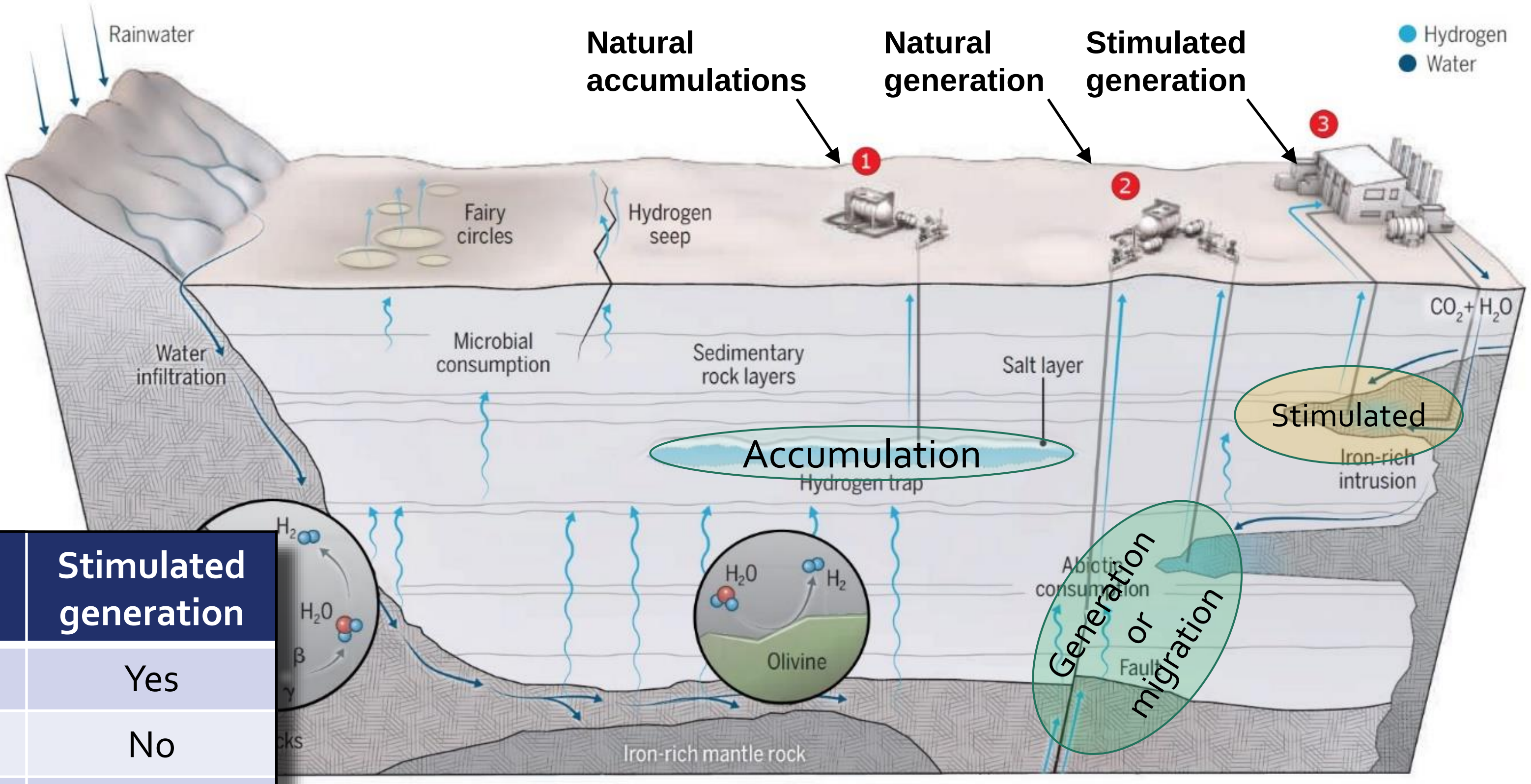
Hydrogen system model – play types

3 conceptual types of exploitable H_2 resources

Hydrogen system model based on the petroleum system

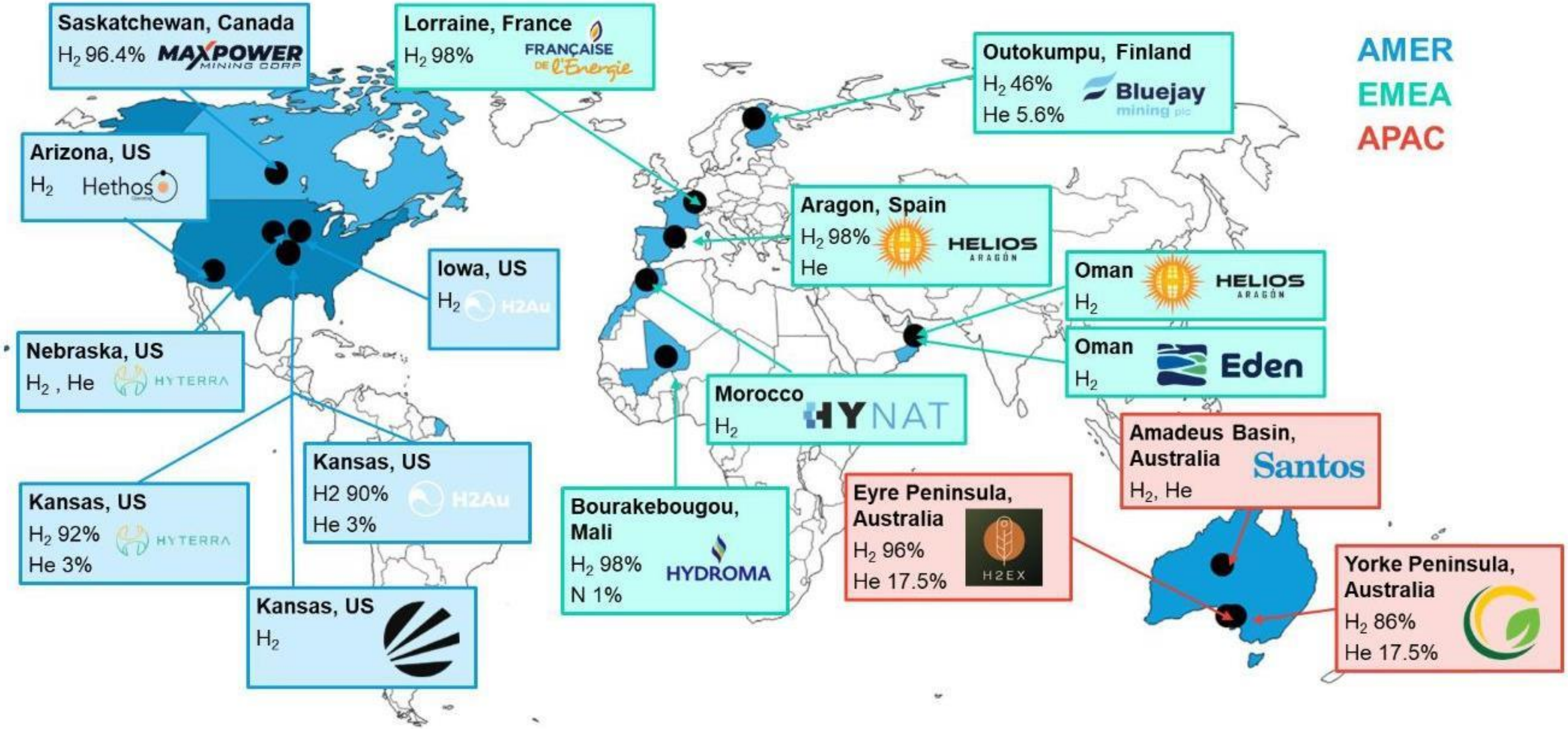
Component	Natural accumulations	Natural generation	Stimulated generation
Source	Yes	Yes	Yes
Migration pathway	Yes	Maybe	No
Reservoir	Yes	No	No
Trap/seal	Yes	No	No
Preservation	Yes	No	No
Timing	Yes	No	No



Modified from Hand, 2023

- Global model only accounts for natural accumulations
- Viability of natural and stimulated generation is unknown
- Focus of exploration and USGS activity is on accumulations

Status of geologic hydrogen exploration in 2024



Source: BloombergNEF. Note: This is not an exhaustive list of projects.

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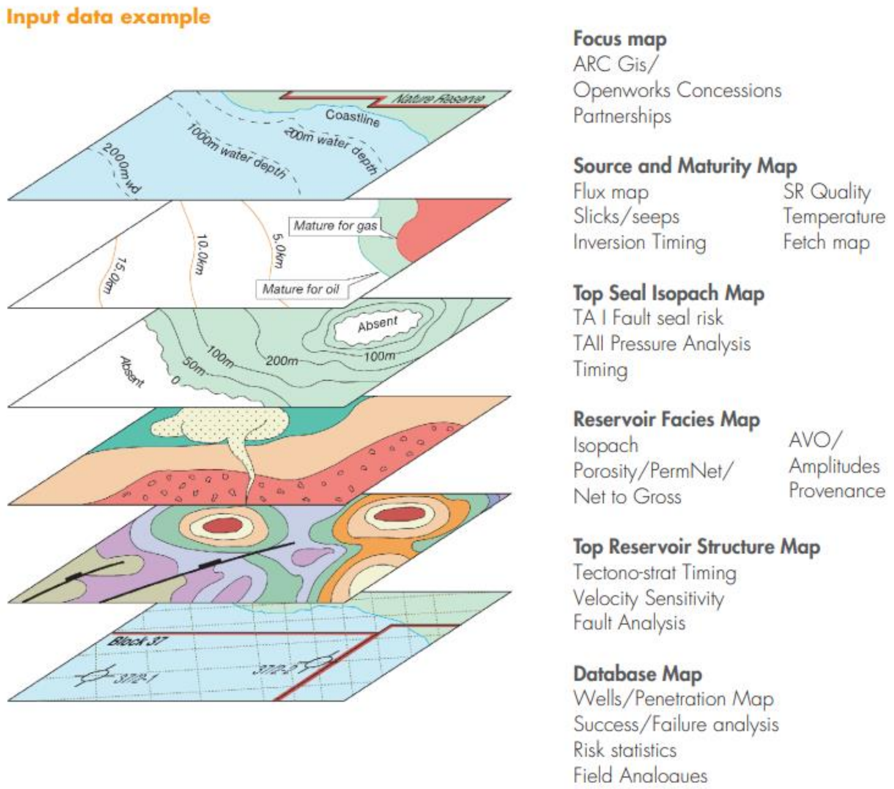
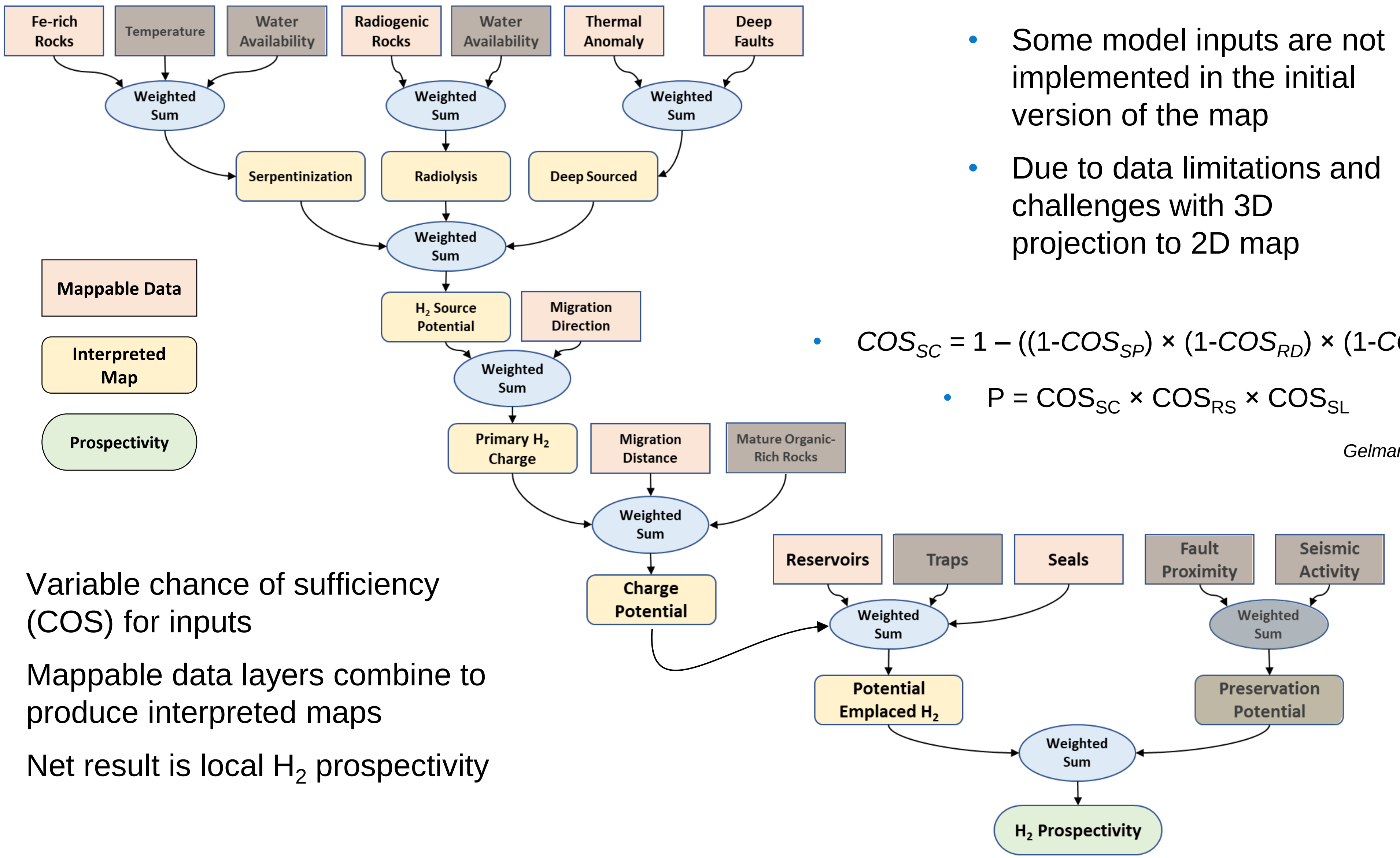
USGS geologic hydrogen prospectivity mapping

- Map geologic hydrogen prospectivity across the United States
- Develop a hydrogen system model for prospectivity mapping
- Identify proxy data sets for each of the essential components of the hydrogen system
- Account for uncertainty in data and the model



Credit: Royal Dutch Shell, AAPG Imperial Barrel Award

Conceptual model for natural hydrogen accumulation



- Some model inputs are not implemented in the initial version of the map
- Due to data limitations and challenges with 3D projection to 2D map

- $COS_{SC} = 1 – ((1\text{-}COS_{SP}) \times (1\text{-}COS_{RD}) \times (1\text{-}COS_{DP}))$
  - $P = COS_{SC} \times COS_{RS} \times COS_{SL}$

Gelman et al., 2025

- Variable chance of sufficiency (COS) for inputs
- Mappable data layers combine to produce interpreted maps
- Net result is local H_2 prospectivity

Data Inputs

Component		Layer	Chance of Sufficiency			Buffer	Migration
			COS Low	COS Mid	COS High		
Source	Serpentinization	SP1: East Coast Magnetic Anomaly	0.7	0.8	0.9	no	yes
		SP2: Surface Ultramafics	0.6	0.7	0.8	20 km	no
		SP3: Failed Rifts	0.7	0.8	0.9	no	yes
		SP4: Geophysical Anomalies	0.1	0.4	0.7	no	yes
		SP5: All Other Areas	0.0	0.1	0.2	no	no
	Radiolysis	RD1: Uranium Deposits	0.1	0.2	0.3	10 km	yes
		RD2: Uranium Favorable	0.0	0.05	0.1	10 km	yes
		RD3: Precambrian Craton	0.5	0.7	0.9	100 km	no
		RD4: Accreted Terranes	0.1	0.2	0.5	100 km	no
		RD5: Young Granitoids	0.1	0.2	0.3	20 km	no
	Deep Sources	DP1: Surface Faults	0.1	0.2	0.3	10 km	yes
		DP2: Suture Zones	0.2	0.5	0.8	40 km	yes
		DP3: High Heat Flow	0.5	0.7	0.9	±10 mW/m^2	no
		DP4: All Other Areas	0.0	0.1	0.2	no	no
Reservoir		RS1: Sedimentary Rocks	0.8	0.95	1.0	no	no
		RS2: Non-Sedimentary Rocks	0.7	0.8	0.9	no	no
		RS3: Sedimentary Basins	1.0	1.0	1.0	no	no
Seal		SL1: Salt	0.0	0.1	0.2	no	no
		SL2: Sedimentary Rocks	0.6	0.8	1.0	no	no
		SL3: Non-Sedimentary Rocks	0.2	0.5	0.8	no	no
		SL4: Sedimentary Basins	0.1	0.3	0.5	no	no

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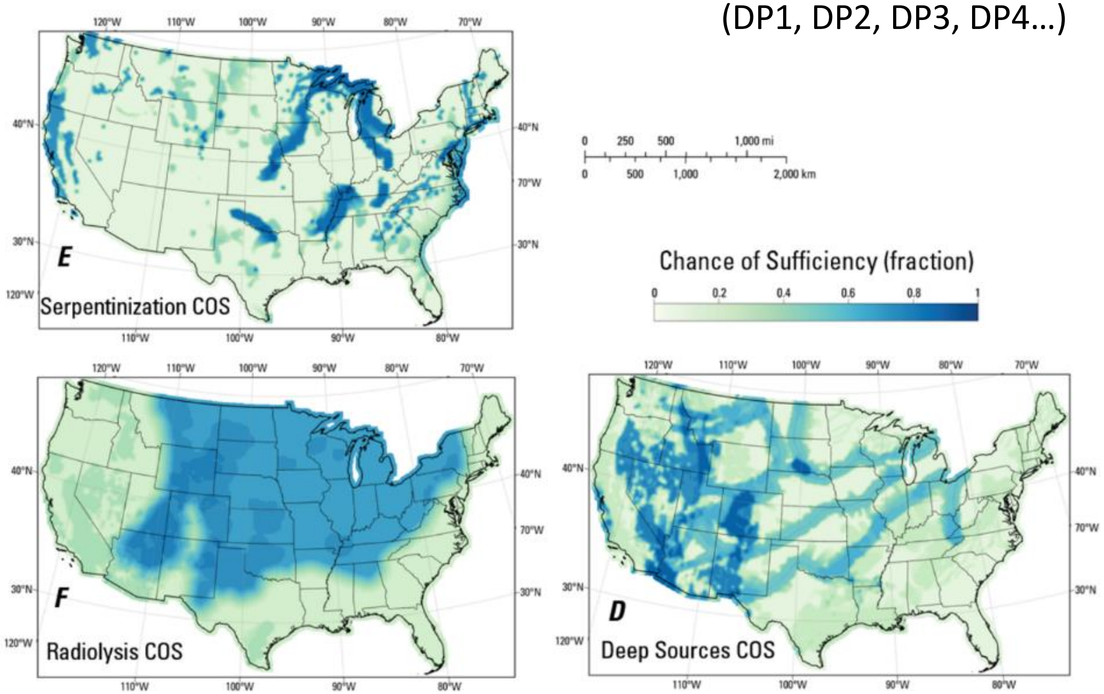
Gelman et al., 2025

Hydrogen system components

Source

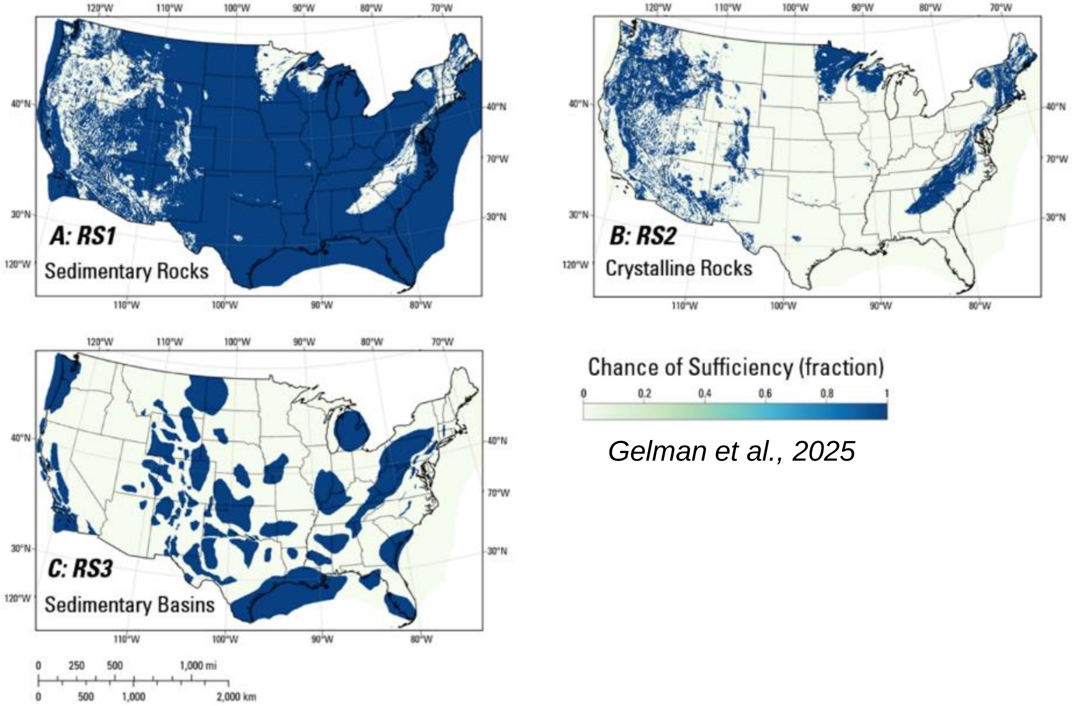
- Serpentinization-type Reactions (SP1, SP2, SP3, SP4, …)
- Radiolysis of H_2O (RD1, RD2, RD3, RD4, …)
- Cryptic “deep sources” (DP1, DP2, DP3, DP4…)



Reservoir | Seal | Preservation

- Sedimentary
- Non-sedimentary

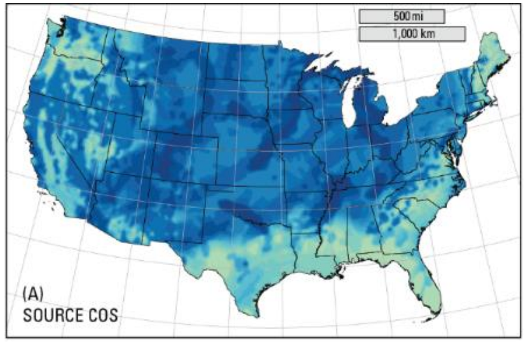
(RS1, RS2, RS3,…)
(SL1, SL2, SL3, …)



Gelman et al., 2025

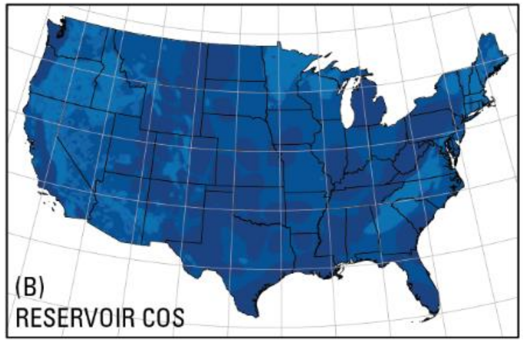
Geologic hydrogen prospectivity

Source COS



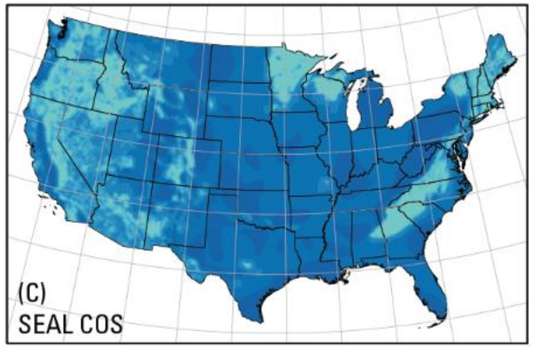
x

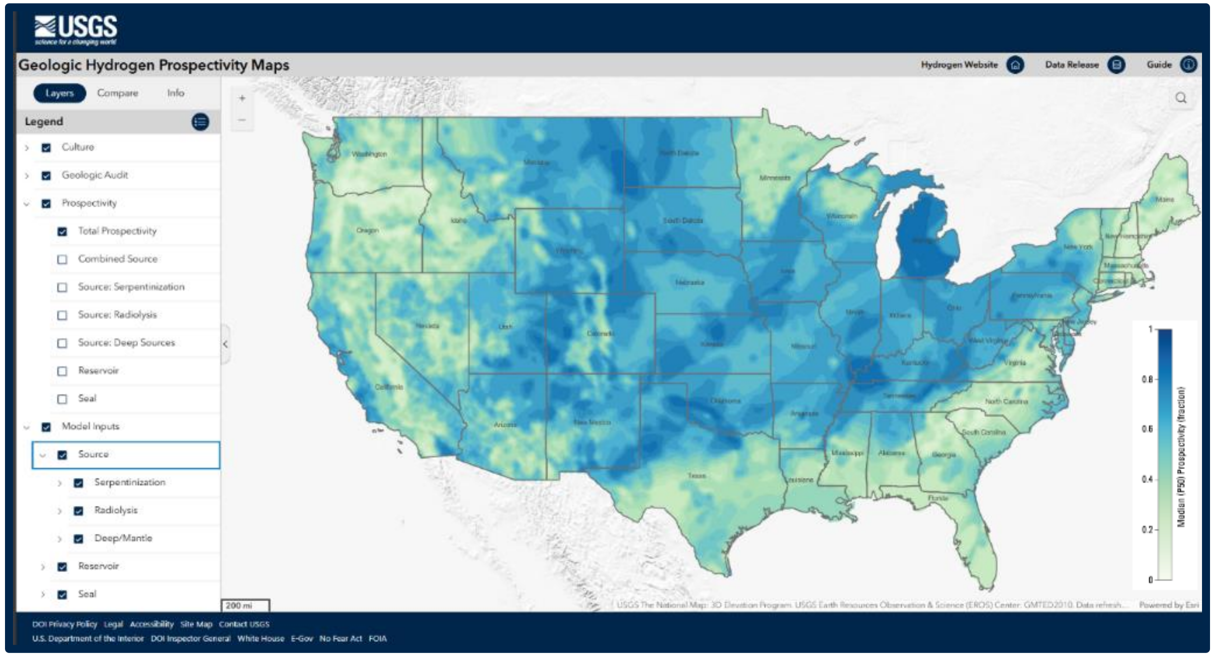
Reservoir COS



x

Seal COS





Gelman et al., 2025

https://www.usgs.gov/publications/prospectivity-mapping-geologic-hydrogen

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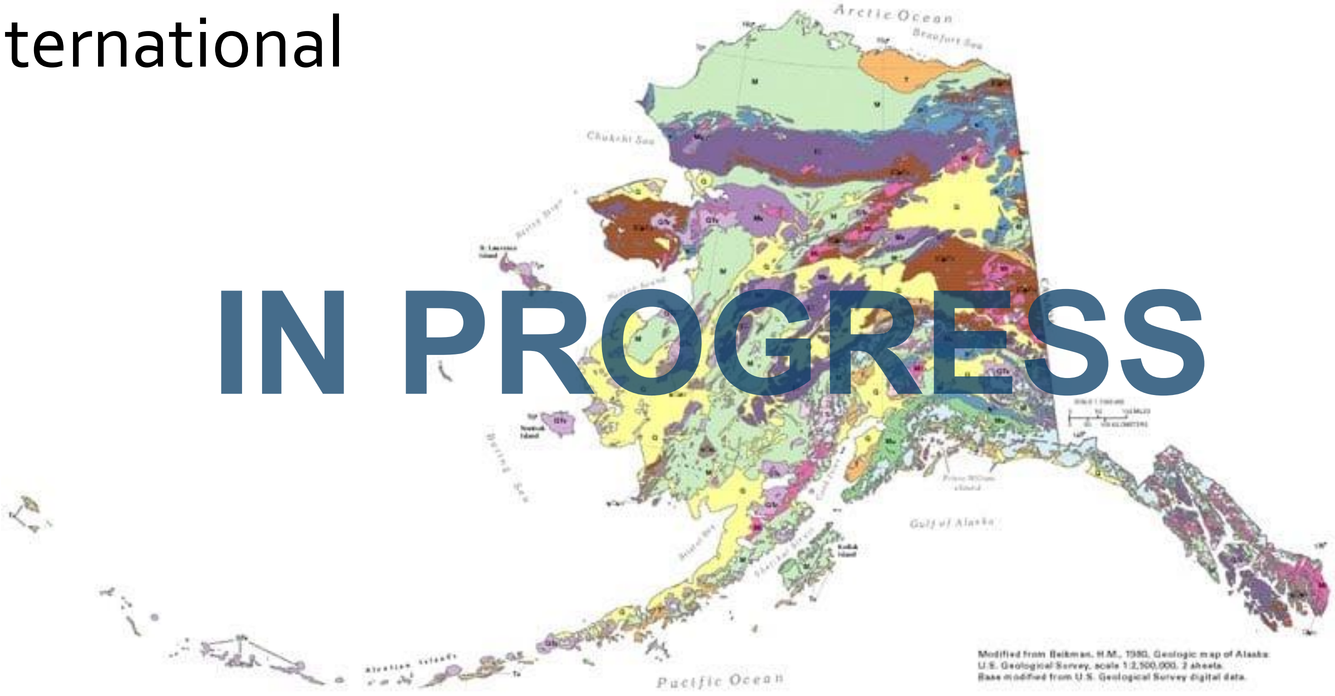
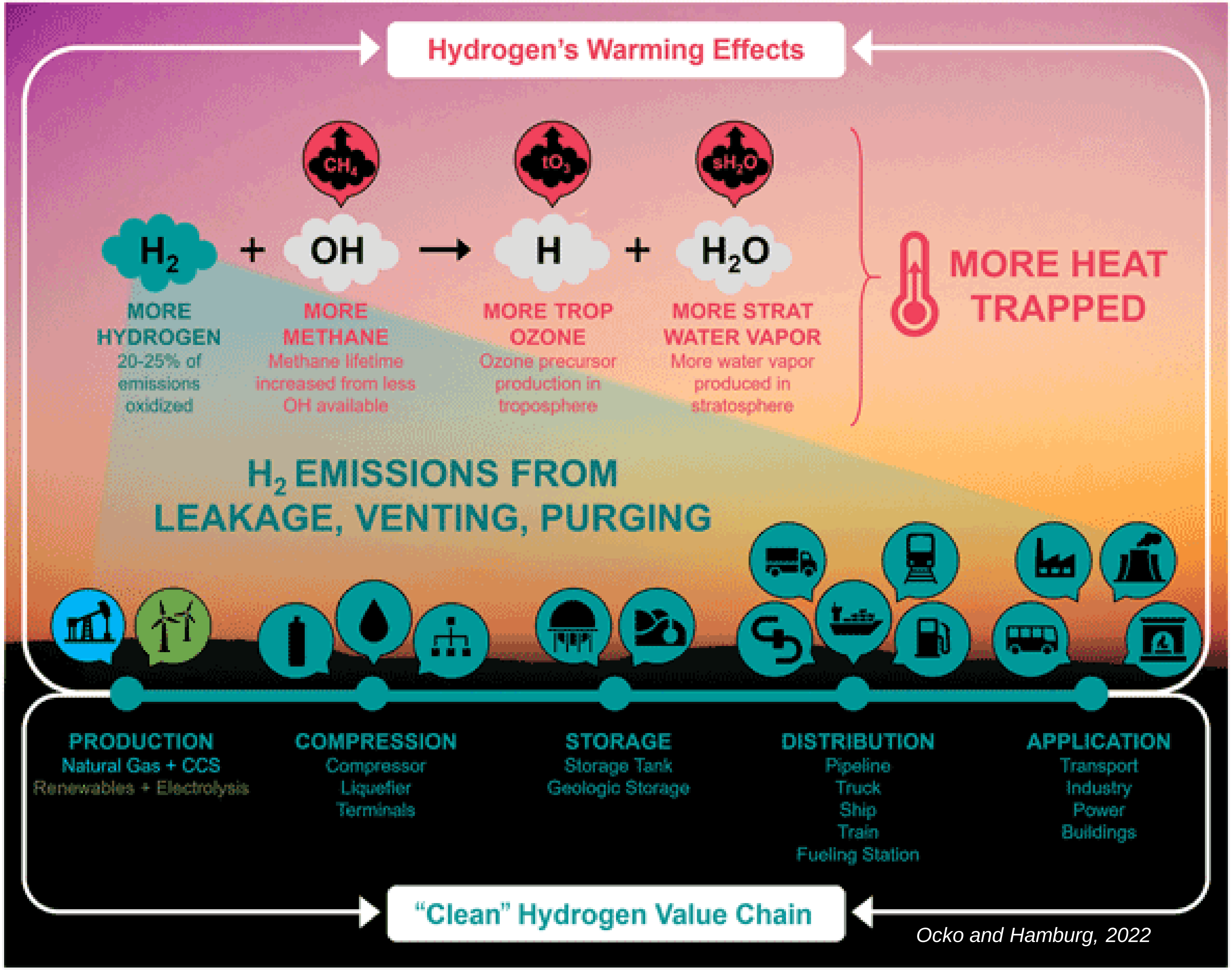
Geologic hydrogen prospectivity mapping status

- Prospectivity mapping of Alaska
- In discussions with international collaborators
  - Canada
  - Australia
  - Brazil
  - Colombia
  - Finland
  - Others …

IN PROGRESS

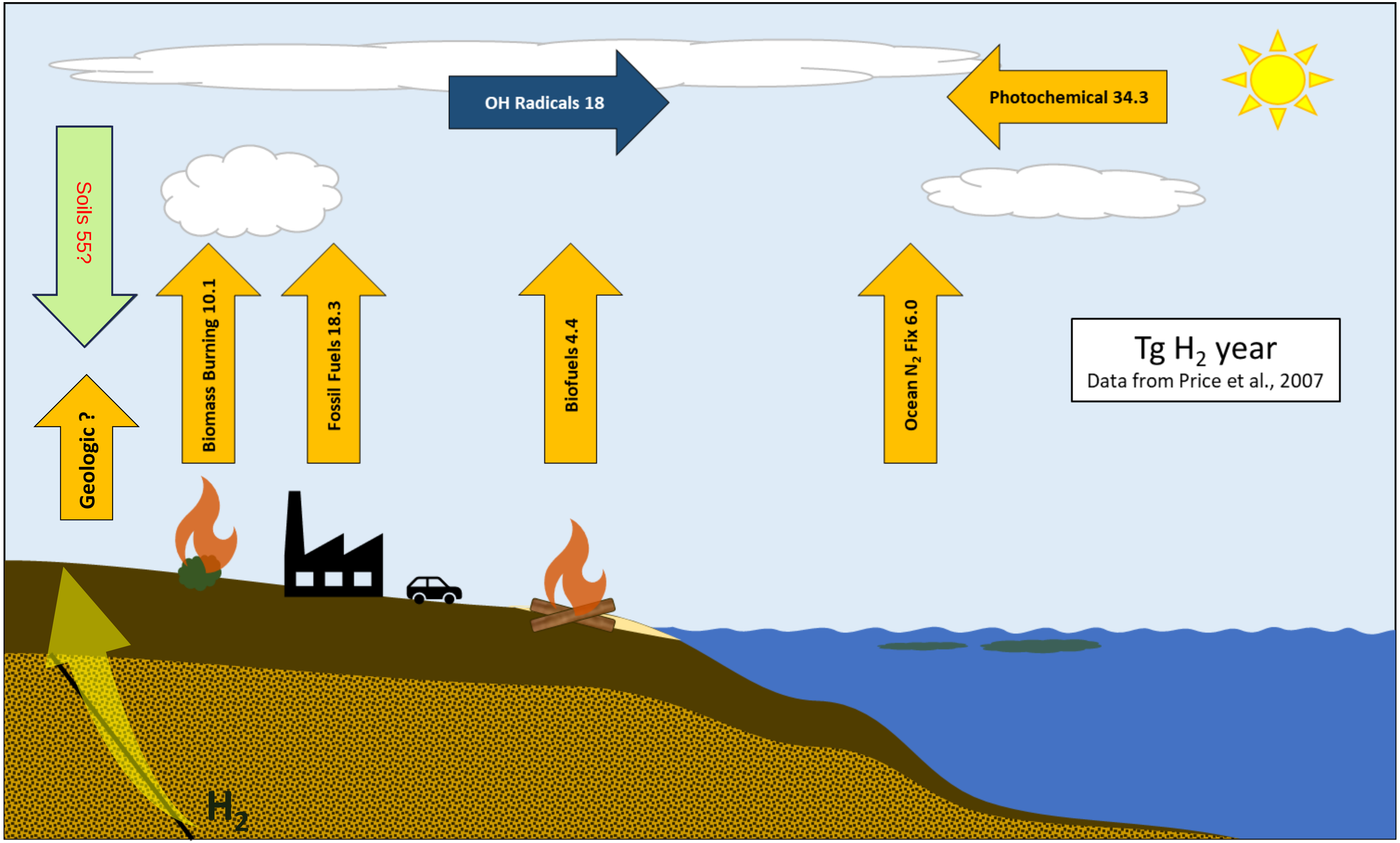


Indirect GHG effect of stray hydrogen



Ocko and Hamburg, 2022

Global hydrogen cycle



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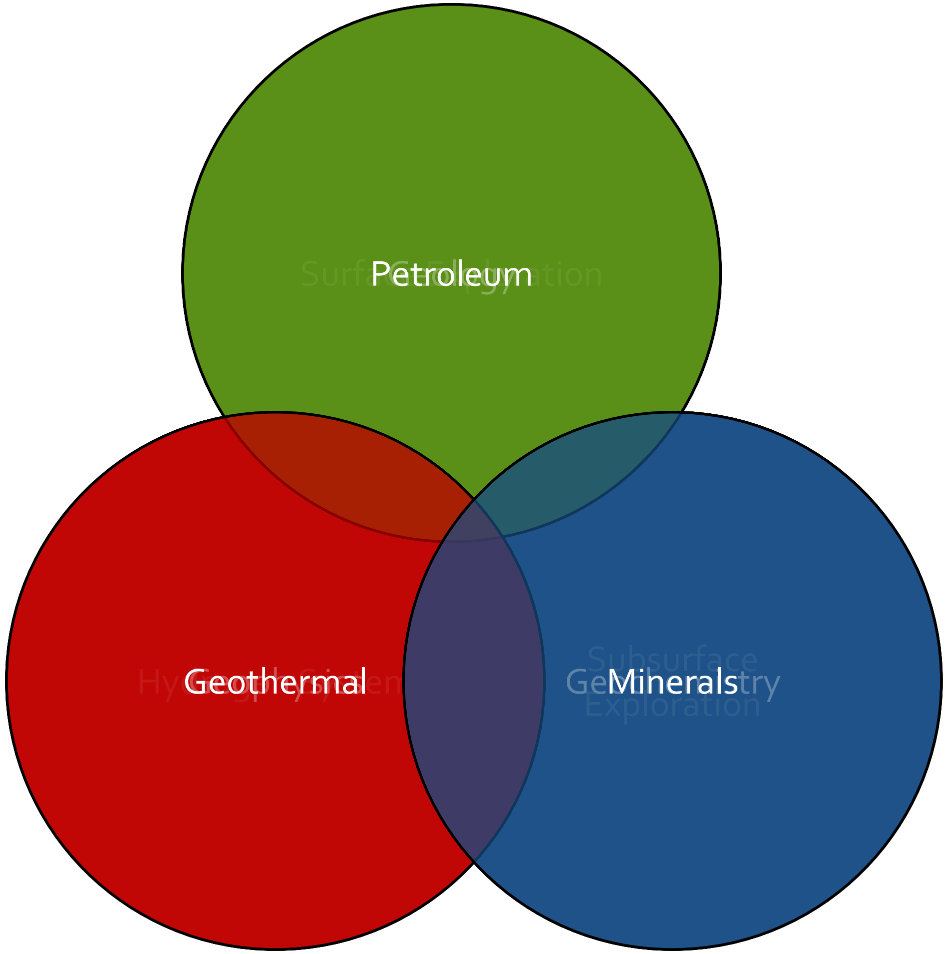
Research needs

- **Refinement of the hydrogen system** model
- Development of **surface** and **subsurface exploration** techniques for identification of hydrogen system components
- Development of **modeling** tools for hypothesis testing and evaluating hydrogen system concepts
- **Engineering** approaches for efficient production of hydrogen from the subsurface
- **Integration of Geology, Geochemistry, and Geophysics**
- Much of the needed **expertise and technology exists** in petroleum, geothermal, and mineral resource fields



Summary

- Large quantities of natural hydrogen exist in the subsurface
- The potential for economic accumulations of hydrogen gas is unknown
- Resource exploration and prospectivity mapping is active around the globe
- Research is needed:
  - To better understand the processes that lead to the accumulation of hydrogen in the subsurface
  - To identify effective exploration techniques and strategies
  - To develop efficient engineering approaches for hydrogen production
  - To better understand the natural global hydrogen cycle

Natural Hydrogen, LLC

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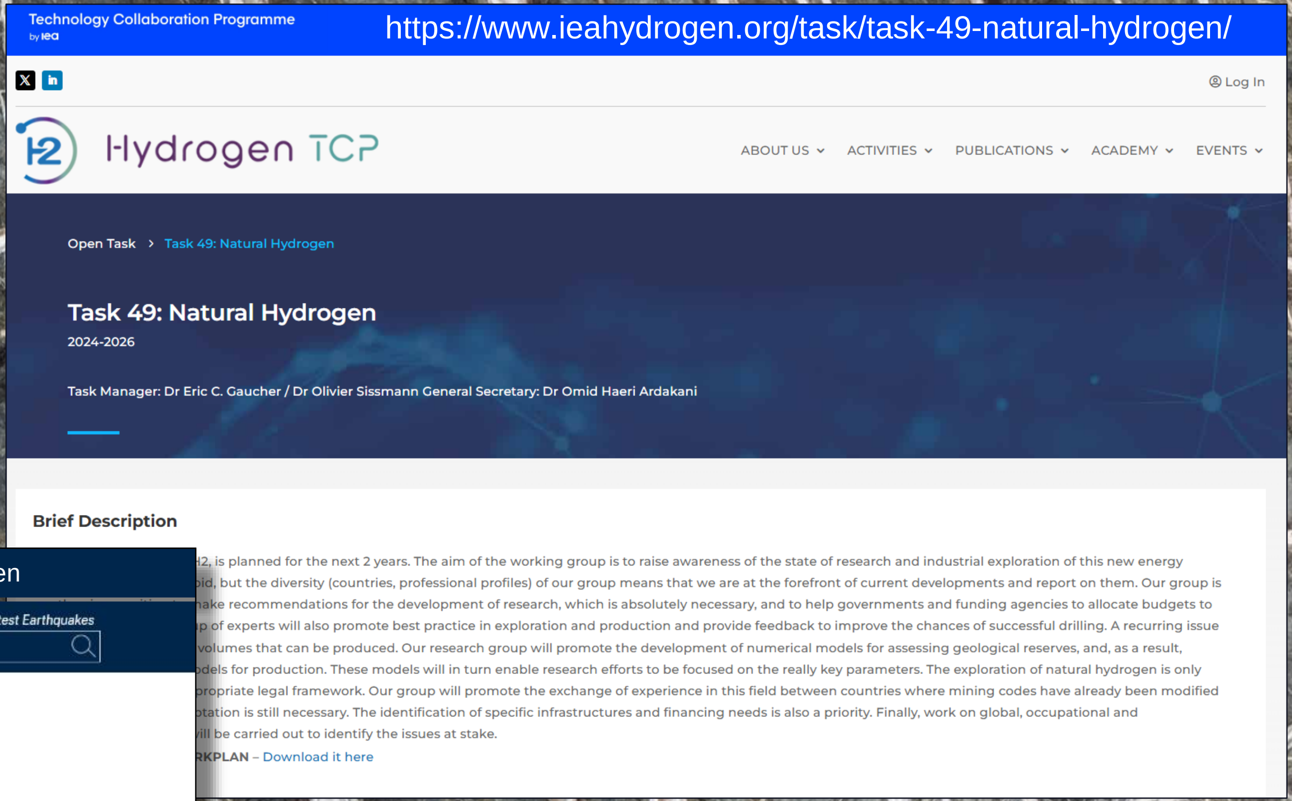
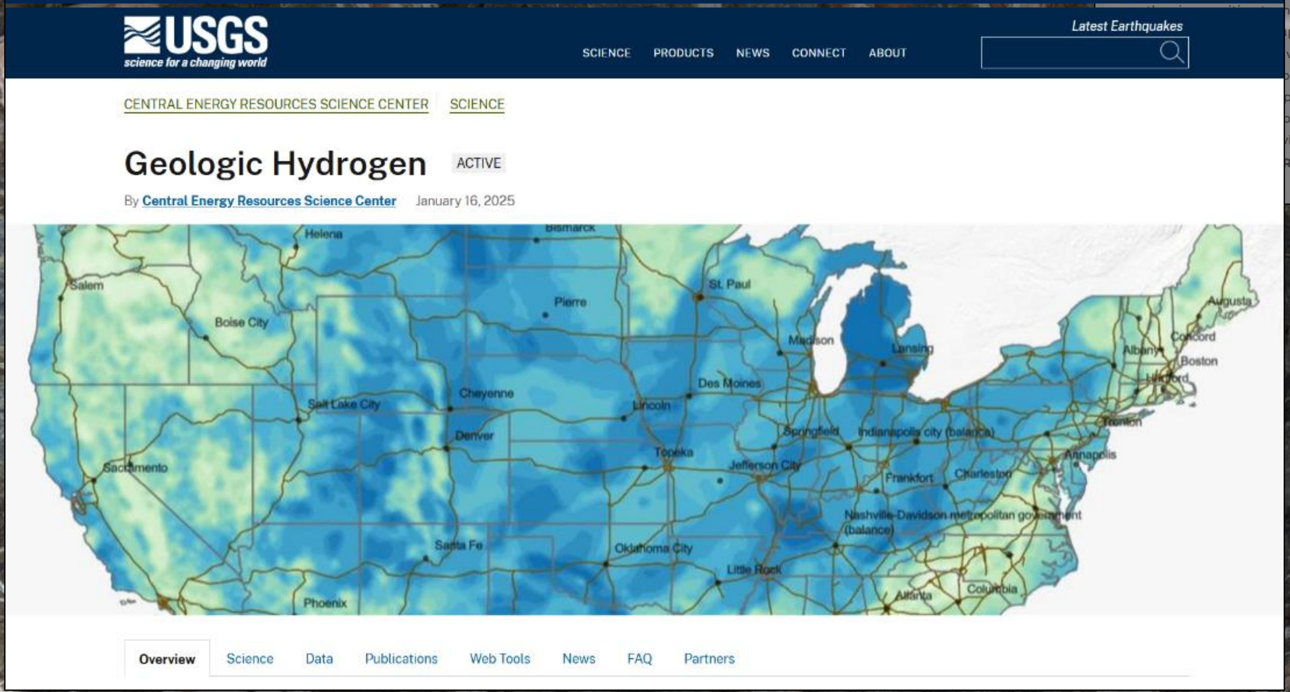
Thank you

https://www.ieahydrogen.org/task/task-49-natural-hydrogen/



https://www.usgs.gov/centers/central-energy-resources-science-center/science/geologic-hydrogen



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Thank you

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