REPORT ON THE 2024 GEOLOGIC HYDROGEN WORKSHOP

PREPARED BY THE US ARCTIC RESEARCH COMMISSION
JANUARY 2025

Report on the 2024 Geologic Hydrogen Workshop
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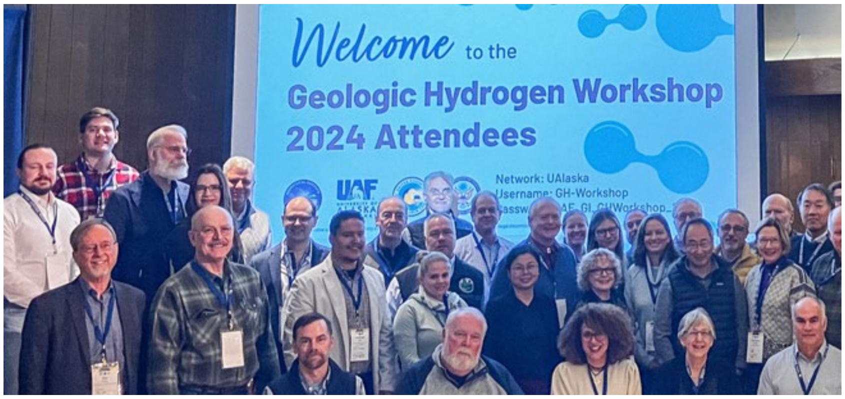
Geologic hydrogen in Alaska: an overlooked carbon-free fuel

December 2024

Goal: Increase federal coordination and research investment to assess the potential of geologic hydrogen as a significant energy resource the United States, including Alaska.

Why?: Federal science and resource agencies have not recognized geologic hydrogen's potential as an energy resource. Alaska's geologic hydrogen could provide a significant economically and environmentally preferred fuel in areas outside the North Slope and Cook Inlet.

Introduction



Alaska holds great promise as a source of "geologic hydrogen," a low-cost, previously overlooked, below-ground, natural energy resource. The hydrogen gas can be "burned" to produce clean energy, and the only byproduct is water.

This new opportunity is based on information exchanged during a workshop at the University of Alaska Fairbanks (UAF), on October 29-31, 2024 that brought together over 100 leaders from the private sector (oil and gas, mining, investment), state, federal, and non-US governments, academia, and private foundations (e.g., Gates Foundation's Breakthrough Energy).

A list of participants (**Appendix A**), select photos (**Appendix B**), a meeting agenda (**Appendix C**), and media reports on the workshop from the *Alaska Dispatch News* and *Alaska Business News* (**Appendix D**) are attached.

The workshop, hosted and sponsored by the US Arctic Research Commission (USARC) and UAF's Geophysical Institute, and co-sponsored by the Department of State's Office of the Ambassador-at-Large for Arctic Affairs, was organized by Dr. Mark Myers (USARC), Dr. Geoff Ellis (US Geological Survey) and Mr. Steve Masterman (UAF-Geophysical Institute).

The **outcomes** from the workshop include key findings about the potential new energy resource in Alaska, that would be accessed by conventional drilling, and recommendations for basic and applied research that would help identify prospective drilling locations, and to assess the potential to artificially stimulate below-ground hydrogen gas production such that the resource could be considered renewable. Specific recommendations are in **Appendix E**.

> ***"It could be gigantic or it could be a bust, but if it's really there... wow!"***
>
> - **Bill Gates** comments on geologic hydrogen to *The Economist*, December 2023

Background


A methane and hydrogen seep on Mount Chimaera in Turkey has burned for centuries.

Most hydrogen used today in the global energy system is manufactured from other energy sources such as natural gas or coal. When used as an energy source, this manufactured hydrogen costs significantly more than natural gas and produces carbon dioxide as a byproduct. Hydrogen can also be generated by electrolysis of water using renewable energy sources, but this uses more energy than then the hydrogen will provide. For hydrogen to become a major energy source, a cheaper alternative source may be required, and that may be geologic or naturally occurring hydrogen.

Scientists have recently discovered that hydrogen gas, formed naturally by geological processes deep within the Earth, accumulates in deposits and can be accessed and recovered by drilling, and then burned to produce energy or converted to useful products such as ammonia (fertilizer).

Better yet, this geologic hydrogen is continuously generated by chemical and geological processes when subsurface water reacts with iron-rich igneous rocks. This produces an oxidation-reduction chemical reaction, which releases hydrogen gas and creates serpentine minerals (e.g., talc and magnetite) and fluids. Studies suggest that 30% of today's annual hydrogen demand (23 Mt/year) is produced, annually, through "serpentinization." If a relatively small amount of this hydrogen gas is naturally trapped in reservoirs, over time, the amount of hydrogen gas that could be economically produced through drilling conventional wells would meet projected global demand for several hundred years.

Because of its purity, geologic hydrogen, also referred to as "natural," or "gold," or "white" hydrogen could play a big role in the global transition to clean energy. Based on drilling in Africa, Europe, Australia, and the lower 48, new companies (including Koloma, a 2023 startup funded with $91M from Bill Gates, and now with over $500M of investments), have sprung up with the goal of finding and extracting natural hydrogen gas.

While there are geological settings in Alaska, and the broader Arctic region that may be conducive to producing natural hydrogen, which are typically not associated with oil and gas deposits, they have yet to be studied and assessed by geologists.

Hydrogen can be used to power vehicles, ships, planes, power generators, and other industrial applications. Natural hydrogen can be produced at a lower price and with lower energy (less carbon) than other types of hydrogen, including that created from renewable energy.

Workshop findings

- The October 29-31, 2024 geological hydrogen workshop was initiated by the US Arctic Research Commission, and co-sponsored with the University of Alaska Fairbanks, the Geophysical Institute, and the Department of State's Office of the Ambassador-at Larger for Arctic Affairs, brought together federal and state research, resource agencies, and elected officials, an Alaska Native corporation, mining and oil and gas companies, international and national universities, and agencies. There was broad support for building a sustained research effort for geologic hydrogen in Alaska and beyond.

- Outside of a small community of experts in government and industry, geologic hydrogen's potential is not yet understood and therefore appreciated. Workshop participants became more optimistic and favorably inclined toward accelerated research and exploration after being provided with insight into the science, engineering, and potential economics and scale of the resource.

- Recent analysis from the Department of Energy's Advanced Research Projects Agency - Energy (ARPA-E) indicates that geologic hydrogen could be produced at lower cost than other hydrogen production methods such as methane steam reforming with carbon sequestration or electrolysis, or from renewable energy sources.

- Worldwide investment in research and exploration activities is rapidly increasing including in Europe, Middle East, and Australia. Private sector investment is in jurisdictions where regulatory permitting, licensing and baseline geoscience data are available.

- The US Geological Survey is completing the first geologic hydrogen assessment of the continental US and is beginning an assessment of Alaska. Awareness in federal resource agencies such as the Bureau of Land Management and the Bureau of Ocean Energy Management appears to be minimal, and the federal regulatory structure needed to manage geological hydrogen has not been developed.

- The geology of Alaska is highly favorable for geologic hydrogen. Of particular interest are areas in and near known and potential critical mineral and strategic mineral deposits and near remote interior and coastal communities.

- A well-coordinated sustained national research program could dramatically and rapidly decrease the current high levels of uncertainty around the potential of this resource in the United States, including Alaska as well as assure that the United States has a leadership role in the development of this global resource.

- The wide variety of potential sources for generating geological hydrogen, coupled with the high cost of energy which limits both mining and community development and the presence of a skilled mining, oil and gas, federal state, native corporation and university workforce creates a great opportunity for developing a global testbed for increasing the understanding of the potential of geological hydrogen as an economic and environmentally preferred energy source.

- Research and exploration for geologic hydrogen is rapidly increasing in the continental US in states including Kansas, Nebraska and Iowa, in Canada, Europe, Australia, and China. Alaska is about two years behind but with a sustained effort could catch up. Without a systematic research program as well as a permissive regulatory regime Alaska will not be able to attract private sector investment.

Federal government efforts include:

a. **USGS**: Developed a global resource model, which will be published in 2025, to predict how much geologic hydrogen might be in the subsurface. The USGS is now mapping regions in the lower 48 most likely to have geologic conditions conducive to subsurface hydrogen accumulation. An initial assessment in Alaska will begin in July 2025.

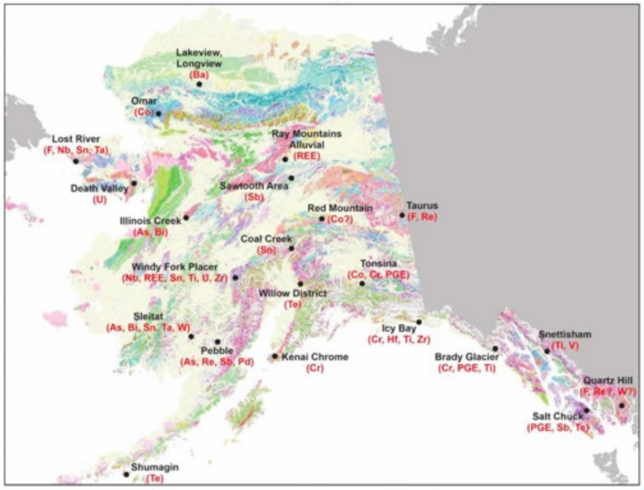
b. **ARPA-E**: Awarded $20M to 16 projects in February 2024 to explore geologic hydrogen stimulation and reservoir management. Released a request for information (RFI) on geologic hydrogen resource exploration (here), due December 2, 2024.

c. **US Air Force**: Conducting market research to explore whether geological hydrogen exists under Air Force installation lands, where it exists, and whether extraction is economically and technologically feasible. Released a RFI (here) for geological hydrogen resource assessment and characterization.

d. **US Arctic Research Commission**: encouraging research on geologic hydrogen.

Implications for Alaska

- Discovery of significant accumulations of geologic hydrogen in Alaska could transform Alaska's energy, economic, and environmental future.
- Alaska has not yet been mapped for geologic hydrogen. First effort is on lower 48.
- Based on Alaska's geology, many areas are likely to be prospective for geologic hydrogen accumulations.



Select Significant Critical Mineral Occurrences

- If found, hydrogen could be used as "green power" for mines, transportation (air, sea, and land) and for rural community heat and power.

Needed in Alaska

- Geologic setting studies
- Search for hydrogen seeps
- More focused geological field work
- Resource assessment methodology, then assessments
- Licensing regimes for federal and state government
- Research and exploration drilling
- Transportation and storage studies
- Economic feasibility studies
- Environmental studies

Appendix A: Participants

Last Name	First Name	Position / title	Organization
Ackerman	Chris	VP Corporate Development	Stillwater Critical Minerals
Acosta	Marisa	Assistant Professor of Economic Geology	University of Alaska Fairbanks
Arola	Teppo	Chief Expert	Geological Survey of Finland (GTK)
Bechberger	Melody	Petroleum Geologist	SOA DNR Division Oil and Gas
Becker	Kevin	Policy Fellow	Office of Representative Peltola
Bickford	Barb	Owner and Principal	Bickford Collaboration
Bishop	Click	Senator	Alaska Legislature
Boyce	Rod	Science communicator/public information	UAF Geophysical Institute
Boyle	John	Commissioner	State of Alaska, Dept. of Natural Resources
Buurman	Helena	Research Development Officer	University of Alaska Fairbanks
Clarke	David	Engineering Director	Alaska Marine Power (AMP)
Coakley	Bernard	Professor	Geophysical Institute
Conley	Don	Subsurface Storage Portfolio Manager	Sandia National Laboratories
Crowther	John	Deputy Commissioner	Alaska Department of Natural Resources
Dashevsky	SAM	Exploration Manager	NORTHERN ASSOCIATES INC.
Dickson	Debra	Administrative Officer	US Arctic Research Commission
Donaldson	Ed	DOI/BOEM - Chief, Resource Analysis	Bureau of Ocean Energy Management
Eicken	Hajo	Director	International Arctic Research Center, UAF
Ellis	Geoffrey	Research Geologist	US Geological Survey
Englert	Taylor	Mine operator/ owner	Englert Mining
Espinosa	Rick	CEO	Dominion Oil and Mineral Exploration
Fan	Long	Assistant Professor	UAF
Farrell	John	Executive Director	US Arctic Research Commission
Farris	Stuart	Founder	Hestia Energy
Fisher-Goad	Sara	Executive Director of Operations	UAF - Office of the VCR
Freeman	Curt	President	Avalon Development Corp.
Garcia	Stephen	Petroleum Engineer	Bureau of Land Management
Gelman	Sarah	Geologist	U.S. Geological Survey
Giessel	Catherine	Alaska State Senator	Alaska Senate
Gillis	Robert	Geologist	Alaska Division of Geological & Geophysical Surveys
Gooch	Brad	Head Geologist	Serpentine Resources
Goodrum	Brent	Deputy Commissioner	Dept of Natural Resources
Gooley	Jared	Research Geologist	U.S. Geological Survey
Graham	Nathan	Advanced Instrumentation Laboratory Manager	Geophysical Institute
Greenwell	Alanna	Communications and Public Outreach Coordinator	Vice Chancellor for Research office
Haas	Mary	Venture Partner	Breakthrough Energy Ventures
Haeri Ardakani	Omid	Research Scientist	Geological Survey of Canada
Hanson	Matthew	Geologist	Doyon Limited
Harrison	Simon	Commercial Director	Alaska Marine Power LLC
Hartman	Richard	Chief Innovation Officer	Air Force Office of Energy Assurance

Harun	Nina	Geologist	Division of Geol. & Geoph. Surveys, State of AK
Hasiuk	Franek	Research Geologist	Sandia National Laboratories
Hinzman	Larry	President's Arctic Professor	University of Alaska Fairbanks
Hofmann	Florian	Research Assistant Professor	Geophysical Institute, UAF
Hosford Scheirer	Allegra	Research Scientist	Stanford University
Huerta	Nicolas	Research Scientist / Group Leader	Pacific Northwest National Laboratory
Ivey	Mark	UAF Temp Faculty, Sandia Labs (ret,)	UAF
Johnson	Tim	CEO	Granite Creek Copper
Jones	Jamey	Earth MRI Science Coordinator	US Geological Survey
Karolyte	Ruta	Principal Product Scientist	Snowfox Discovery
Kasper	Jeremy	ACEP Director	UAF
Kennedy	David	Commissioner,	US Arctic Research Commission
Knicely	Joshua	Post Doctoral Researcher	Univeristy of Alaska Fairbanks / Fairbanks Climate Action Coalition
Konishi	Yusaku	Director General, Technology Department	Japan Organization for Metals and Energy Security (JOGMEC)
Kreiner	Doug	Associate Center Director, Geology	USGS Alaska Science Center
La Belle-Hamer	Nettie	UAF Vice Chancellor for Research	University of Alaska Fairbanks
Larsen	Jessica	Professor	University of Alaska, Fairbanks
Larson	Toti	Research Associate and Principal Investigator	Murock Systems Research Laboratory, Un. of Texas
Li	Yaoguo	Professor	Colorado School of Mines
Long	Joshua	Geologist	Alaska Division of Geological & Geophysical Surveys
Mabry	Monte	Senior Staff Geophysicist	U.S. Department of the Interior, BLM
Maercklein	Will	Petroleum Engineer	Bureau of Land Management
Masterman	Steven	Deputy Director Alaska Critical Minerals Collaborative	UAF Geophysical Institute
McCabe	Kevin	House Representative	Alaska State Legislature
McCoy	Bob	Director, Geophysical Institute	University of Alaska Fairbanks
McKinley	Paul	Arctic Energy Advisor	ACEP / U.S. DOE Arctic Energy Office
Meggitt	Dallas	Technical Director	Sound & Sea Systems, LLC
Milad	Benmadl	Geophysicist III	Oklahoma Geological Survey, Un. of Oklahoma
Miller	Lance	VP Natural resources	NANA Regional Corp
Misarti	Nicole	Director	Institute of Northern Engineering
Munk	Lee Ann	Director Alaska Critical Minerals Collaborative	UAF GI
Myers	Mark	Commissioner	US Arctic Research Commission
Myers	Alice	volunteer	self employed
O'Hayer	Walter	Senior Geologist	Santos
Paine	Haley	Deputy Director	Alaska Division of Oil and Gas
Prisco	Nathan	Faculty	Alaska Center for Energy and Power
Pu	Xiaofei	Researcher	National Renewable Energy Laboratory
Qureshi	Kamil	Geologist III	Alaska DNR
Riley	Rocky	president/owner	Tolovana Construction Co
Salisbury	Barrett	Earthquake & Tsunami Hazards Program Manager	AK Div. of Geological & Geophysical Surveys
Schaefer	Carl	Geologist	Northern Associates, Inc
Schell	Matthew	Deputy Assoc. Dir. Research & Analysis	Ted Stevens Center for Arctic Security Studies
Schmitt Foudhil	Hadjira	Research Associate	US Arctic Research Commission

Schnabel	Bill	Dean	UAF College of Engineering and Mines
Seol	Yongkoo	Supervisory Research Scientist	UD DOE, National Energy Technology Laboratory
Sheets	Brent	Director, Petroleum Development Lab	Institute of Northern Engineering/UAF
Steefel	Carl		Lawrence Berkley Lab
Sung	Nancy	Assistant Director, Polar Sciences	Office of Science and Technology Policy (OSTP)
Swan	Monte	Co-Founder MagmaChem Research Institute	MagmaChem Research Institute
Tape	Carl	Professor of Geophysics	UAF
Templeton	Alexis	Professor	University of Colorado
Todd	Erin	Research Geologist	USGS
Trainor	Tom	Professor	UAF
Treadwell	Mead	Owner	Treadwell Development
Turner	Andrew	Research Chemist	USGS
Twelker	Evan	Geologist	State of Alaska DGGS
Werdon	Melanie	Director and State Geologist	Alaska Geological & Geophysical Surveys
White	Mark	Senior Research Engineer	Kansas Geological Survey
Whitney	Erin	Director, Arctic Energy Office	U.S. Department of Energy
Wicks	Douglas	Program Director	DOE ARPA-E
Wilbur	Sara	Communications Coordinator	UAF Geophysical Institute
Wilcox	JR	CEO	Alyeschem
Zhang	Mengli	Research Assistant Professor	Colorado School of Mines
Zhao	Allen	CEO	Hestia Energy

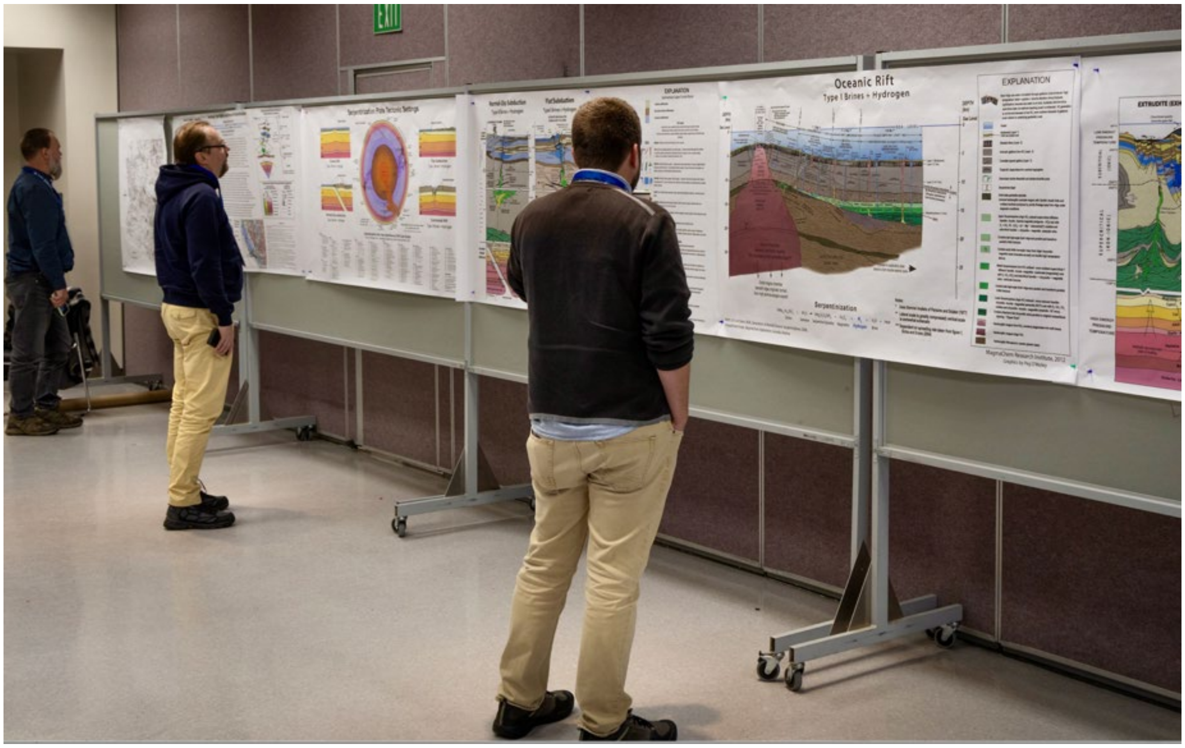
Appendix B: Photos

Dr. Mike Sfraga, US Ambassador At-Large for Arctic Affairs, a co-sponsor of the workshop, also co-sponsored by the US Arctic Research Commission, the Univ. of Alaska Fairbanks and the Geophysical Institute. (John Farrell)

Dr. Mark Myers, USARC, moderating a panel including AK Sen. Cathy Giessel, John Crowther, Deputy Commissioner, DNR, Lance Miller, NANA, and AK Sen. Click Bishop. (Eric Marshall)

Mr. Steve Masterman, UAF, moderating a panel including Lance Miller, NANA, AK Sen. Cathy Giessel, Richard Hartman, USAF, and John Boyle, Commissioner, DNR. (John Farrell)

Participants included Hon. Mead Treadwell, David Kennedy, USARC, and Dr. Bob McCoy, Director, Geophysical Institute (Eric Marshall)



Geological hydrogen poster session. (Eric Marshall)

Audience of over 100 registrants at the geological hydrogen workshop. (Eric Marshall)

Appendix C: Final Agenda

Could Geologic Hydrogen Transform Alaska's Energy Future?

October 29-31, 2024
University of Alaska Fairbanks

Day 1 – October 29, 2024

8:00 - 8:30 **Arrival, Coffee and Tea**

8:30 - 8:35 **Welcome Remarks** – Dr. Mark Myers, Commissioner, United States Arctic Research Commission

[Video Day 1 Welcome]

8:35 - 9:45 **Agreements and Roundtable Introductions** – Ms. Barb Bickford, Principal, Bickford Collaboration

[Video Day 1 Introduction Starts at Timestamp 7:58]

Bickford Presentation

[PDF Presentation Day 1 Welcome]

Round Table Introductions

[PDF Handout Roundtable Introductions]

9:45 - 10:00 **BREAK/Opening polls**

What is the primary question you've brought to this workshop?
Which sentence describes how much you know about geologic hydrogen?
Is it likely Geologic Hydrogen will be a significant source of energy in Alaska?

Poll Results

[PDF Day 1 Opening Slido Questions FINAL]

10:00 - 10:15 **Remarks on Geologic Hydrogen**

Dr. Mark Myers, Commissioner, United States Arctic Research Commission

[Day 1 Introductory Remarks Starts at Timestamp 26:51]

The Honorable Lisa Murkowski, United States Senate

[Pre-recorded Video]

Dr. Michael Sfraga, Ambassador At-Large for the Arctic Affairs

[Video Day 1 Starts at Timestamp 30:24]

Dr. Nancy Sung, Assistant Director for Polar Science, the White House Office of Science and Technology Policy

[Video Day 1 Starts at Timestamp 37.25]

10:15 - 10:20 **Agenda Review** – Mr. Steve Masterman, Deputy Director of the Alaska Critical Minerals Collaborative at Geophysical Institute, University of Alaska Fairbanks

[Video Day 1 Starts at Timestamp 43:30]

10:20 - 11:05 **Session 1 – Geologic Hydrogen Systems** (Moderator – Dr. Nettie Labelle Hamer, UAF)
[Video Day 1 Starts at Timestamp 49:35]

Dr. Geoff Ellis, USGS, Examples of Geologic Hydrogen Systems
[Video Day 1 Starts at Timestamp 54:30]
[Power Point Presentation by Dr. Geoff Ellis]

Dr. Sarah Gelman, USGS, Geologic hydrogen assessments in the US & Alaska
The presenter has asked that the video and presentation not be shared.

Dr. Greeshma Gadikota, Cornell, Current Analytical and assessment tools
[PDF Presentation by Dr. Greeshma Gadikota]
The presenter has asked that the video not be shared.

Session 1 Questions from Participants
[Summary of Questions to Speakers Day 1 Session 1]

11:05 - 11:30 **Session 1 Discussion** – Ms. Barb Bickford
No Links to Video Or Presentation

11:30 - 12:15 **LUNCH**

12:15 - 1:05 **Session 2 – Geologic Hydrogen Generation** (Moderator – Dr. Jamey Jones, USGS)
[Video Day 1 Introduction Starts at Timestamp 1:16:30]

Monte Swan, MagmaChem Research Institute, Geologic Hydrogen and the Process of Serpentinization
[Video Day 1 Starts at Timestamp 1:19:47]
[Power Point Presentation by Dr. Monte Swan]

Dr. Ruta Karolyte, Snowfox Discovery, Radiolytic Hydrogen: Generation and Release
The presenter has asked that the video and presentation not be shared.

Dr. Andrew Turner, USGS, Chemical /Isotopic Signature of Generated Gasses
[Video Day 1 Starts at Timestamp 1:31:17]
[Power Point Presentation by Dr. Andrew Turner]

Session 2 Questions and Answers
[Video Day 1 Starts at Timestamp 1:41:57]
[Summary of Questions to Speakers Day 1 Session 2]

1:05 - 1:25 **Session 2 Discussion** – Ms. Barb Bickford
No Links to Video Or Presentation

1:25 - 1:30 **BREAK**

1:30 - 2:20 **Session 3 – Alaskan Geology and Geologic Hydrogen, Part 1** (Moderator – Dr. Michael West, UAF)
[Video Day 1 Starts at Timestamp 1:53:31]

Dr. Barrett Salisbury, DGGS and **Dr. Carl Tape, UAF,** Alaska Tectonics and Crustal Scale Faults
[Video Day 1 Starts at Timestamp 1:57:12]

[Power Point Presentation by Dr. Barrett Salisbury]

Dr. Jessica Larsen and **Dr. Marisa Acosta, UAF,** Modern Alaska Subduction & Serpentinization Conditions
[Video Day 1 Starts at Timestamp 2:08:44]
[Power Point Presentation by Drs. Jessica Larson and Marisa Acosta]

Dr. Elisabeth Nadin, **UAF**, Preserved Alaskan Subduction Zones
[Video Day 1 Starts at Timestamp 2:20:21]
[Power Point Presentation by Dr. Elisabeth Nadin]

Session 3 Questions and Answers
[Video Day 1 Starts at Timestamp 2:32:14]
[Summary of Questions to Speakers Day 1 Session 3 Q & A]

2:20 - 2:40 **Session 3 Workshop Activity:** Human Spectrograms – Ms. Barb Bickford
No Links to Video Or Presentation

2:40 - 3:00 **BREAK**

3:00 - 3:50 **Session 4 – Alaskan Geology and Geologic Hydrogen, Part 2** (Moderator – Dr. Melanie Werdon, DGGS)
[Video Day Starts at Timestamp 2:44:22]

Dr. Erin Todd, USGS, Alaska Mafic and Ultramafic Rock Compositions & Distribution
The presenter has asked that the video and presentation not be shared.

Dr. Sue Karl, USGS, Alaska U-Th-K Mineral Occurrences
The presenter has asked that the video and presentation not be shared.

Session 4 Questions and Answers
[Video Day 1 Starts at Timestamp 2:49:39]
[Summary of Questions to Speakers Day 1 Session 4 Q&A]

3:50 - 4:00 **Session 4 Discussion** – Ms. Barb Bickford
No Links to Video Or Presentation

4:00 - 5:00 **Summary of Day 1: Fishbowl Discussion** – Ms. Barb Bickford
[Video Day 1 Starts at Timestamp 2:53:56]

5:30 - 6:30 **AAPG 2024-2025 Distinguished Lecture**
Dr. Geoffrey Ellis, USGS, Natural Hydrogen: An Overlooked Potential Energy Source
[Video, Distinguished Lecture by Dr. Geoffrey Ellis]
[PDF Presentation by Dr. Geoffrey Ellis]

Day 2 – October 30, 2024

8:00 - 8:30 **Arrival, Coffee and Tea**

8:30 - 8:40 **Welcome** – Dr. Mark Myers, Commissioner, United States Arctic Research Commission
[Video Day 2 Welcoming Remarks]

8:40 - 9:05 **Top Insights Poll and Conversations** – Ms. Barb Bickford
Question to Participants: What are top insights from Day 1 that should be shared with everyone?
[Video Day 2 Starts at Timestamp 6:39]

9:05 - 9:10 **Agenda Review** – Mr. Steven Masterman

9:10 - 10:00 **Session 5 – Migration, Preservation & Production of Geologic Hydrogen** (Moderator – Dr. Haley Paine, AK DOG)
[Video Day 2 Starts at Timestamp 10:59]

Dr. Joshua Long, DGGS, Potential Traps or Storage Areas in Alaska
[Video Day 2 Starts at Timestamp 16:07]
[Power Point Presentation by Dr. Joshua Long]

Dr. Franek Hasiuk, Sandia National Lab, Conditions for Preservation and Storage of Geologic Hydrogen
[Video Day 2 Starts at Timestamp 28:01]
[Power Point Presentation by Dr. Franek Haisuk]

Dr. Alexis Templeton, University of Colorado Biological Consumption of Hydrogen
[Edited PDF Presentation by Dr. Alexis Templeton]
The presenter has asked that the video not be shared.

Session 5 Questions and Answer Session
[Video Day 2 Starts at Timestamp 39:42]
[Summary of Questions to Speakers Day 2 Session 5]

10:00 - 10:20 **Session 5 Discussion** – Ms. Barb Bickford
No Links to Video Or Presentation

10:20 - 10:35 **BREAK**

10:35 - 11:30 **Session 6 – Geologic Hydrogen Research, Part 1** (Moderator – Dr. Robert McCoy, UAF)
[Video Day 2 Starts at Timestamp 1:07:27]

Dr. Geoffrey Ellis, USGS, Historical Context and Overview of the Rest of the World
[Video Day 2 Starts at Timestamp 1:12:06]
[Power Point Presentation by Dr. Geoffrey Ellis]

Dr. Doug Wicks, DOE / ARPA-E, Overview of North American Research
[Video Day 2 Starts at Timestamp 1:21:13]
[Power Point Presentation by Dr. Doug Wicks]

Dr. Omid Ardakani, Geological Survey of Canada, Overview of Canadian Research
[Video Day 2 Starts at Timestamp 1:34:49]
[Power Point Presentation by Dr. Omid Ardakani]

Dr. Teppo Arola, Geological Survey of Finland, Natural hydrogen research example from Finland

[Video Day 2 Starts at Timestamp 1:44:05]
[Power Point Presentation by Dr. Teppo Arola]

Session 6 Questions and Answers

[Video Day 2 Starts at Timestamp 1:52:31]
[Summary of Questions to Speakers Day 2 Session 6]

11:30 - 11:45 **Session 6 Discussion** – Ms. Barb Bickford

No Links to Video Or Presentation

11:45 - 12:45 **LUNCH**

12:45 - 1:45 **Session 7 – Geologic Hydrogen Research, Part 2** (Moderator – Dr. Barbara Ransom, NSF)

[Video Day 2 Starts at Timestamp 2:01:04]

Dr. Shuvajit Bhattacharya, BEG, University of Texas, Austin *(virtual),* Geophysical Exploration and Volumetric Estimates of Mafic and Ultramafic Rocks in Alaska: Implications for Geologic and Stimulated Hydrogen

The presenter has asked that the video and presentation not be shared.

Dr. Yaoguo Li, Colorado School of Mines, Geologic Hydrogen Exploration and Reserve Estimation: The Role of Geophysics

[Edited PDF Presentation by Drs. Yauguo Li and Mengli Zhang]
The presenter has asked that the video not be shared.

Dr. Toti Larson and Esti Ukar, Bureau of Economic Geology, University of Texas, Austin, Subsurface Hydrogen Research at the Texas Bureau of Economic Geology

[Video Day 2 Starts at Timestamp 2:08:16]
[Power Point Presentation by Dr. Toti Larson and Esti Ukar]

Dr. Mengli Zhang, Colorado School of Mines, The impact of industry-driven consortium on geologic H2 research and potential contribution to Alaska through geophysical exploration

[PDF Presentation by Drs. Mengli Zhang and Yauguo Li]
The presenters have asked that the video not be shared.

Session 7 Questions and Answers

[Video Day 2 Starts at Timestamp 2:19:35]

1:45 - 2:00 **Session 7 Discussion –** Ms. Barb Bickford
What might Alaska research contribute to the global effort, both in science and in energy policy?

[Video Day 2 Starts at Timestamp 2:23:54]

2:00 - 2:15 **BREAK**

2:15 - 3:15 **Session 8 – Resource Development and Potential Future Relevance of Geologic Hydrogen** (Moderator – Dr. Lance Miller, Vice President NANA)

[Video Day 2 Starts at Timestamp 2:31:24]

Dr. Erin Whitney, Director Arctic Energy Office, Department of Energy, Geologic Hydrogen and the Department of Energy

[Video Day 2 Starts at Timestamp 2:38:56]
[Power Point Presentation by Dr. Erin Whitney]

Dr. Richard Hartman, Office of Energy Assurance, CIO USAF, Geologic Hydrogen

[Power Point Presentation by Dr. Richard Hartman]
The presenter has asked that the video not be shared.

Commissioner John Boyle, Alaska Department of Natural Resources, Resource Development and Potential Future Relevance of Geologic Hydrogen

[Video Day 2 Starts at Timestamp 2:56:42]
The presenter did not provide a copy of the presentation to share

Session 8 Questions and Answers

[Video Day 2 Starts at Timestamp 3:15:47]

3:15 - 4:15 **Session 8 Next Steps Activity** – Ms. Barb Bickford

No Links to Video Or Presentation

4:15 - 4:55 **Summary of Day 2/Group Reflection (Fishbowl)** – Ms. Barb Bickford

Regarding geologic research in AK between now and 2030, what would progress look like?

[Video Day 2 Starts at Timestamp 3:24:06]

4:55 - 5:00 **Closing** – Mr. Steve Masterman

No Links to Video Or Presentation

Day 3 – October 31, 2024

8:00 - 8:30 **Arrival, Coffee and Tea**

8:30 - 8:50 **Welcome and Agenda Revisions –** Dr. Mark Myers Commissioner, United States Arctic Research Commission

[Video Day 3 Welcome]

8:50 - 9:20 **Dr. Doug Wicks, DOE / ARPA-E,** Economics of Hydrogen

[Video Day 3 Starts at Timestamp 3:51]
Presenter did not grant permission to share Presentation

9:20 - 10:20 **Session 9 – Utility, Economics, Storage and Transportation of Hydrogen** (Moderator – Ms. Gwen Holdmann, UAF)

[Video Day 3 Starts at Timestamp 27:10]

Mr. JR Wilcox, Alyeschem, North Slope Hydrogen Conversion

[Video Day 3 Starts at Timestamp 38:48]
[Power Point Presentation by Mr. JR Wilcox]

Mr. David Clarke, AMP, Cook Inlet Hydrogen Generation and Storage

[Video Day 3 Starts at Timestamp 38:58]
[Power Point Presentation by Mr. David Clarke]

Dr. Mead Treadwell, Principal Treadwell Development, North Slope Hydrogen for Export

[Video Day 3 Starts at Timestamp 1:00:13]
[Power Point Presentation by Dr. Mead Treadwell]

Mr. Timothy Johnson, Stillwater Critical Minerals, Hydrogen in the Duke Island / Stillwater

[Video Day 3 Starts at Timestamp 1:13:22]
Presenter did not grant permission to share Presentation

Session 9 Questions and Answers

[Video Day 3 Starts at 1:25:26]
[Summary of Questions to Presenters Day 3 Session 9]

10:20 - 10:40 BREAK

10:45 - 11:45 Session 10 – Policy & Regulation Needed for Research & Exploration
(Moderator – Dr. Mark Myers, United States Arctic Research Commission)

[Video Day 3 Starts at Timestamp 1:29:36]

Senator Cathy Giessel, Co-Chair Alaska Senate Natural Resources Committee

[Video Day 3 Starts at Timestamp 1:37:34]
Presenter did not have a Power Point Presentation

Senator Click Bishop, Co-Chair Alaska Senate Natural Resources Committee

[Video Day 3 Starts at Timestamp 1:46:31]
Presenter did not have a Power Point Presentation

Dr. Lance Miller, Vice President Lands, NANA Regional Corporation

[Video Day 3 Starts at Timestamp 1:50:30]
[PDF Presentation by Dr. Lance Miller]

Deputy Commissioner John Crowther, Alaska Department of Natural Resources

[Video Day 3 Starts at Timestamp 2:00:00]
Presenter did not have a Power Point Presentation

Session 10 Questions to Presenters from Participants

[Video Day 3 Starts at Timestamp 2:08:50]

1:00 - 2:30 Session 11 - Discussions of topics suggested by participants

[Video Day 3 Starts at Timestamp 2:33:55]
[Summary of Discussion Topics Suggested by Participants for Session 11]

2:30 -- 2:35 Closing – Dr. Mark Myers, Commissioner, United States Arctic Research Commission

[Video Day 3 Starts at Timestamp 2:53:20]

2:35 - 4:30 Networking

***The videos of the Workshop are on the USARC YouTube channel*:**

Appendix D: Media coverage

Geologic hydrogen may be an answer to questions, both economic & environmental

https://www.adn.com/alaska-news/science/2024/11/08/geologic-hydrogen-may-be-an-answer-to-questions-both-economic-and-environmental/

By Ned Rozell | Alaska Science. ADN Published: November 8, 2024

Natural hydrogen gas may be trapped under the surface of Alaska in many areas, such as here in the Brooks Range. (Photo by Ned Rozell)

The internal combustion engine is less than 100 years old. Same for the technologies we have developed to pull oil and gas from the ground.

It's hard to imagine life without our cars and planes and buildings heated with natural gas and oil. But it really wasn't that long ago that people had none of these things. Sometimes, advances happen, and clever people change the way we live.

A group met at the University of Alaska Fairbanks last week to brainstorm a possible new economy for Alaska and clean energy source for the world — geologic hydrogen.

We bump into hydrogen every second of our lives. It's a colorless, odorless, explosive gas that is the most abundant element in the universe, making up about 75% of everything.

Including you. Hydrogen constitutes 10% of your body mass as it combines with oxygen to make water, which makes up about 65% of you.

But all those scientists were not gathered in a Fairbanks ballroom to talk about whether human hydrogen might power a gold mine in the Bush. They were interested in hydrogen that may be trapped underground by the types of rocks that also trap gas and oil.

Mark Myers thinks Alaska might be a great place to find this geologic hydrogen. At an age when many people retire and with a resume line that includes "Director, U.S. Geological Survey," one might wonder why he cared enough to travel to Fairbanks to gather geologists and policymakers.

Because, he said after the meeting, pivoting to an energy source that emits only water vapor when burned would solve so many problems.

Like the existential one of humanity blowing past the stop sign of planet-heating carbon levels in the atmosphere. As well as the question of what might power Alaska's economy after gas and oil.

Mark Myers, head of the U.S. Arctic Research Commission, leads a discussion on the potential of geologic hydrogen at a conference in Fairbanks recently. Alaska state Sen. Cathy Giessel takes notes. (Photo by Eric Marshall / UAF Geophysical Institute).

Myers is a geologist who earned his doctorate at UAF and then went to work for the state of Alaska as a petroleum geologist, where he roamed all over the state and Canada looking at rocks.

President George W. Bush interrupted Myers' field career when he tapped him as the 14th director of the USGS in 2009. Myers and his wife, Alice, lived in Washington, D.C., until a change of administration led them back to Alaska. Here, then-Gov. Sarah Palin made Myers coordinator of the state's gas line project.

Myers is now commissioner of the U.S. Arctic Research Commission. Wearing that title, he gathered around 100 experts at UAF to see if geologic hydrogen could be the next big thing.

Though manufacturers now produce hydrogen as a fuel, the process emits a lot of carbon dioxide and is expensive to produce. That's what makes a natural source intriguing.

Drilling wells to tap into pockets of hydrogen is not yet common in America. But villagers in Mali, a country in Africa, found a source of hydrogen while unplugging an old water well in 2011. Now harnessed, that hydrogen gas generates electricity for a local village.

People have also found natural hydrogen deposits in Canada, Russia, Australia, Germany, New Zealand and other places. Alaska is a good place to look because it has similar geologic conditions, Myers said.

The downside of harvesting geologic hydrogen gas molecules is that they are hard to find, microbes like to eat them and they scatter when they reach the surface. And, even if people find pockets of them underground, deposits may not be located in convenient places.

The upside of geologic hydrogen: If geologists can find pockets and figure out how to mine them, a hydrogen plant could power a nearby village that now has diesel generators rattling every second of every day. Or, a remote gold mine's power plant could run on fuel that emits only water vapor into the air.

If technology followed that would allow Alaska to become a geologic hydrogen exporter, the state would have an industry that might someday replace oil and gas.

Everyone at the conference agreed that those are all Alaska-size ifs. But a few of those geologists might soon be hiking around Alaska looking for signs of a clean fuel that is part of who we are and the air we breathe and makes up most of the known universe.

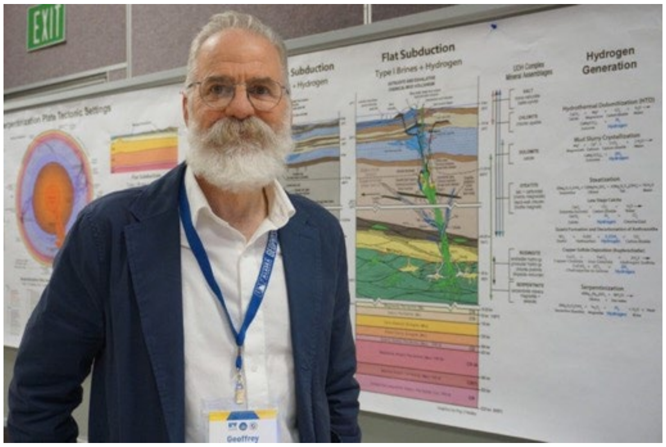
"I'm optimistic we have lit the fire," Myers said.

Alaska scientists and policymakers look to hydrogen as power source of the future

The universe's most common element, which exists in yet-unexplored underground deposits, could underpin a post-oil energy future in Alaska and beyond, experts say

BY: **YERETH ROSEN** - NOVEMBER 15, 2024 5:03 AM

https://alaskabeacon.com/2024/11/15/alaska-scientists-and-policymakers-look-to-hydrogen-as-power-source-of-the-future/



U.S. Geological Survey geologist Geoffrey Ellis stands on Oct. 29 by a poster diplayed at the University of Alaska Fairbanks that explains how pure hydrogen can be pooled in underground formations. Ellis is the leading USGS expert on geologic hydrogen. He was a featured presenter at a three-day workshop on geologic hydrogen that was held at UAF. (Photo by Yereth Rosen/Alaska Beacon)

The key to decarbonization may be all around us.

Hydrogen, the most abundant element in the universe, is in the ocean, in the sky, in the stars, in the bodies of living beings and – of particular importance to energy developers – in the ground.

And it is getting increasing attention globally.

Governments, industry and scientific institutions are now investigating how they might be able to switch from drilling for petroleum, which produces planet-warming carbon dioxide when burned, to drilling for zero-emissions hydrogen.

There are good reasons for that, said Geoffrey Ellis, the U.S. Geological Survey's geologic hydrogen research leader.

Ellis, who said he was once "in the wilderness" on the subject but who is now leading a wide-ranging research group, was one of the main speakers at a geologic hydrogen workshop held in late October the University of Alaska Fairbanks. The event was hosted by the U.S. Arctic Research Commission and the University of Alaska Fairbanks Geophysical Institute and co-sponsored by the Office of the Ambassador at Large for Arctic Affairs, Mike Sfraga.

Shifting to renewable sources like solar, wind and geothermal energy is crucial to addressing climate change, but there is no way those types of energy can power big industrial users like manufacturers and agriculture, Ellis told the workshop attendees.

In the future, Ellis said, there will likely be a need for 400 million tons of hydrogen, compared to the approximately 100 million tons currently used. And the hydrogen currently used is not the type that is pulled from the ground. Rather, it is produced through an energy-consuming process that pulls the element out of other compounds, separating it from methane in natural gas or using electricity to separate it from oxygen in water.

In contrast, the hydrogen in the ground accumulates when water encounters iron or radiation. Through a process known as serpentinization, the reaction with those other elements in the earth separates the water's hydrogen from its oxygen – without human intervention. In contrast with oil and natural gas, which take millions of years to form, geologic hydrogen forms quickly. It can even be stimulated through injection of water.

Initial estimates, Ellis said, are that the earth could hold about 5 million megatons of geologic hydrogen, or 5 billion tons. While much of that is in impossible-to-reach sites like the deep ocean, accessing just 2% of that would meet the anticipated global hydrogen demand for more than 200 years, he told the workshop attendees.

Mark Myers, a member of the U.S. Arctic Research Commission, stands on Oct. by posters explaining how hydrogen can be pooled in underground formations. Myers and others organized a three-day workshop on geologic hydrogen that was held at the University of Alaska Fairbanks. (Photo by Yereth Rosen/Alaska Beacon)

"It's likely that there are large amounts of hydrogen in the subsurface. And so, the question is not: 'Is it down there.' But it's: 'Is it in places where we can find and produce it?'" Ellis said.

For Alaska, where traditional fossil fuels can be expensive as well as environmentally burdensome, hydrogen energy could underpin development of other non-fossil-fuel energy. Geologic hydrogen could be an important part of the solution, said Mark Myers, a geologist and member of the U.S. Arctic Research Commission.

"It's a new resource that could be combined with renewables, but superior in many ways," said Myers, who served in the past as the commissioner of the Alaska Department of Natural Resources, as director of the USGS and as vice chancellor for research at UAF, among other positions.

As he explains it, the physical characteristics that make Alaska prone to earthquakes and volcanic eruptions and rich with mineral deposits also signal potential for reserves of valuable hydrogen in the ground. There is already one company, for example, that is investigating the potential for hydrogen in the same Southeast Alaska geologic belt that holds the better-known Bokan critical minerals deposits currently being explored.

Alaska is far from the only prospective region. Any spot on the earth where the ocean floors have been pulled apart has the potential to hold geologic hydrogen, Myers said.

One region of keen interest is the Midcontinent Rift, a geologic feature that runs from Lake Superior to Kansas in the U.S. Midwest. Exploratory drilling there has already begun.

Still, Alaska has some characteristics that could make it a key area for hydrogen research and development, Myers said.

Alaska, unlike other parts of the nation and the world that are connected to power grids, has some acute energy needs, he said. And it has permafrost, which could be an advantage because microbes that consume hydrogen are less active in cold environments, he said.

There are myriad challenges to geologic hydrogen beyond finding the resource, said experts at the UAF workshop. One is that hydrogen molecules are small, meaning they are not easily trapped in the pores of underground rocks. Another is that hydrogen molecules tend to attach quickly to those of other elements, potentially making separation ephemeral.

For now, there is only one place in the world being powered by geologic hydrogen: Bourakebougou, a small village in Mali. There, hydrogen was discovered in 2011, at a site where in 1987 an errant cigarette touched off an explosion at what was intended to be a water well.

Since then, there have been about two dozen hydrogen wells drilled, and the village's electricity runs off the hydrogen produced from those wells.

U.S. Arctic Research Commission member Mark Myers on Oct. 29 holds a sample of metallic rock from the Bokan formation that could be instrumental in forming geologic hydrogen. The rock samples were displayed at a three-day geologic hydrogen workshop, organized by Myers and others, that was held at the University of Alaska Fairbanks. (Photo by Yereth Rosen/Alaska Beacon)

The idea of replicating anything like that in Alaska is enticing, said a state lawmaker who has been following the subject closely.

Senator Majority Leader Cathy Giessel, R-Anchorage, has immersed herself in the subject of hydrogen. For example, she has been participating in meetings held by the Alaska Hydrogen

Working Group, founded in 2022 by UAF's Alaska Center for Energy and Power and the Department of Energy's Arctic Energy Office.

Geologic hydrogen could be a new source of state revenue, she said. It could provide energy for communities and economic development, she said. If it is found within Native-owned lands, it can enrich Native corporations around the state through the revenue-sharing provisions in the Alaska Native Claims Settlement Act, she said.

But for now, no one should expect any legislation on it, other than potentially some insertions of the word "hydrogen" into existing resource-related statutes if applicable, Giessel said. The subject is too new and there are too many unknowns, she said.

"I don't envision the need for legislation at this point, until we know what the potential resource is," she said.

She does intend to hold at least one informational hearing to help her colleagues and the public get more familiar with the subject, she said.

Providing information is the most important thing the state can do to promote development of geologic hydrogen, Giessel said.

"Probably our biggest help to any industry is if we go out and map what the resource availability is. We are an under-mapped state," she said,

Other information could come from the state's Geologic Materials Center, the collection of cores and other geologic samples that are available for the public to peruse and study, she said. The center, located in Anchorage, is operated by the state Division of Geological and Geophysical Surveys.

Myers, speaking to the experts gathered at the workshop, also emphasized the need to build knowledge – and to do so quickly. That will take a new way of doing science, likely a whole new structure involving government, industry and academia.

"The challenge is great. But it's going to be fun. And you're on the edge of discovery," he told the group.

Correction: This story has been updated to identify Cathy Giessel as Senate majority leader, not president.

https://www.adn.com/business-economy/energy/2024/10/07/could-naturally-occurring-hydrogen-underground-be-a-gusher-of-clean-energy-in-alaska/

Anchorage Daily News (and published in “***Inside Climate News***”)

Could naturally occurring hydrogen underground be a gusher of clean energy in Alaska?

By Hal Bernton
10/7/24

Mark Myers, a commissioner with the United States Arctic Research Commission, photographed on Thursday, Sept. 12, 2024 in Anchorage. Dr. Myers sees geologic hydrogen as a promising path toward reducing global carbon emissions. (Loren Holmes / ADN)

This story is being co-published with Inside Climate News, a nonprofit, non-partisan news organization that covers climate, energy and the environment

Alaska geologist Mark Myers hopes that underground reserves of hydrogen could fuel a new state energy industry.

His dreams were launched by a well drilled in the African country of Mali that yields enough hydrogen to fuel a village electric power plant.

Myers is hopeful that hydrogen deposits also exist in Alaska in a metamorphic rock called serpentinite, which is often found in subduction zones where one plate of the Earth’s crust is pushed underneath another.

“Do we have those source rocks?” Myers asked. “The answer is all over the place. But the big question is how much of this hydrogen gets created—and preserved. We don’t know.”

Myers’ push to find hydrogen reservoirs is driven by his concerns about climate change spurred by fossil fuel combustion. He is convinced that scientific models of a warming Earth are accurate, and justify a concerted effort to move off of coal, oil and gas.

“How is Alaska going to make the energy transition?” he asked. “What is it going to look like in the post-fossil fuel world?”

[Related: Veterans of Alaska’s oil industry look to blaze a renewable energy pathway in the state]

This is blunt talk from a man who spent more than four decades in Alaska’s oil industry and state government, where his resume included service as the chief of the Oil and Gas Division and a stint as the Department of Natural Resources commissioner. He also, under the administration of President

George W. Bush, headed up the U.S. Geological Survey, and is active in academia as a vice chancellor of research at the University of Alaska Fairbanks.

Myers, who currently serves as a presidential appointee to the U.S. Arctic Research Commission, said he gravitated to hydrogen as an energy source that could generate electricity, help the power industry and make transportation fuels.

So far, much of the federal research has focused on ways to make green hydrogen, which can be extracted from water in a process that requires lots of electricity from clean power sources that do not release greenhouse gases. But a potentially cheaper alternative would be reservoirs of naturally forming hydrogen that could be big storehouses of energy. In the U.S. and elsewhere, exploration is now underway to try to find some of those potentially large sources of energy.

The subsurface hydrogen in Mali was discovered in 1987 by well drillers looking for water. Later, more than two dozen boreholes helped to define the boundaries of these reservoirs, which keep recharging with hydrogen. Since 2012, wells producing 98 percent hydrogen gas have provided fuel for the power plant serving the village of Bourakebougou, according to a study of the reservoirs published in 2023 in Nature.

A model developed by the U.S. Geological Survey suggests that underground reservoirs of hydrogen exist in other places, and a company drilling in south Australia has reported significant hydrogen concentrations of more than 90 percent as well as helium in the gases brought to the surface. Technologies also may evolve to harvest hydrogen as it migrates through rock. Another possibility would be injections of water that could stimulate hydrogen production from some formations.

Most of these hydrogen resources are likely to be in areas too deep, too inaccessible or in quantities too small to profitably extract, according to Geoffrey Ellis, a U.S. Geological Survey research geologist, who helped to develop the model. And in some prospective hydrogen reservoirs, the gas may have leaked out or been consumed by microbes.

Still, if a small fraction of these reserves could be tapped, a major new source of carbon-free energy could be developed.

Ellis is now leading an effort to develop maps of the areas in the continental U.S. most likely to contain hydrogen. So far, the top prospects appear to be in the Great Plains and the Atlantic coastal plain.

Myers is eager for the U.S. Geological Survey to develop a similar model that could guide hydrogen exploration in Alaska. In October, he will be joined by Ellis at a three-day hydrogen workshop in Fairbanks jointly sponsored by the Arctic commission and the university's Geophysical Institute.

"The effort now is to pinpoint where it could be," Myers said. "Then, we need to do basic geologic field work. So, start looking at the rocks."

Independent journalist Hal Bernton was a longtime reporter for The Seattle Times, and previously reported for the Anchorage Daily News and The Oregonian. Reach him at hbernton@gmail.com.

Exploring for white hydrogen in SE Alaska

https://www.miningnewsnorth.com/story/2024/11/01/news/exploring-for-white-hydrogen-in-se-alaska/8770.html

10/31/24, by Shane Lasley

Granite Creek assembles the catalyst-rich projects, scientific expertise to become a first mover in the geological hydrogen space.

A belt of rocks spanning the Southeast Alaska Panhandle hosts at least a dozen prospects and deposits enriched with nickel, copper, and platinum group metals (PGM) needed for the energy transition. Could these projects also host hidden stores of geological hydrogen that could offer a clean-burning fuel for the 21st century? Granite Creek Copper Ltd. believes they could and has acquired two Southeast Alaska PGM projects with "white hydrogen" potential.

An element that only emits water vapor when burned, hydrogen is seen by many as a game-changing clean energy fuel of the 21st century. However, hydrogen has the paradoxical distinction of being the most abundant element in the universe, yet very rare in its pure form here on Earth.

Being the lightest of elements on the periodic table, any pure hydrogen on Earth tends to escape the atmosphere. Most of the hydrogen that remains is locked up with other elements in water, hydrocarbons, and other forms.

Splitting hydrogen from water or natural gas, however, requires a lot of energy that comes with both financial and carbon emissions costs.

The grey hydrogen currently being split off natural gas for fertilizers, chemicals, and steel production costs about $2 per kilogram to produce and has a significant carbon footprint that cuts into its clean energy fuel potential.

Green hydrogen, which is split off of water molecules using renewable, does not come with inherent CO2 emissions but costs around $7/kg to produce – way too expensive to be a practical solution to fueling global commerce.

"If you get hydrogen at a dollar a kilo, it's competitive with natural gas on an energy-price basis," said Douglas Wicks, a program director at the U.S. Department of Energy's Advanced Research Projects Agency-Energy (ARPA-E).

Geological hydrogen, a process that involves iron-rich rock formations producing hydrogen naturally, could be the solution.

The U.S. Geological Survey estimates there are potentially billions of tons of geologic hydrogen, also known as white hydrogen, buried in the Earth's crust.

Granite Creek believes that PGM projects in Alaska and British Columbia have the right conditions to host hidden deposits of geological hydrogen and has acquired two such projects on the Southeast Alaska Panhandle – Duke Island and Union Bay.

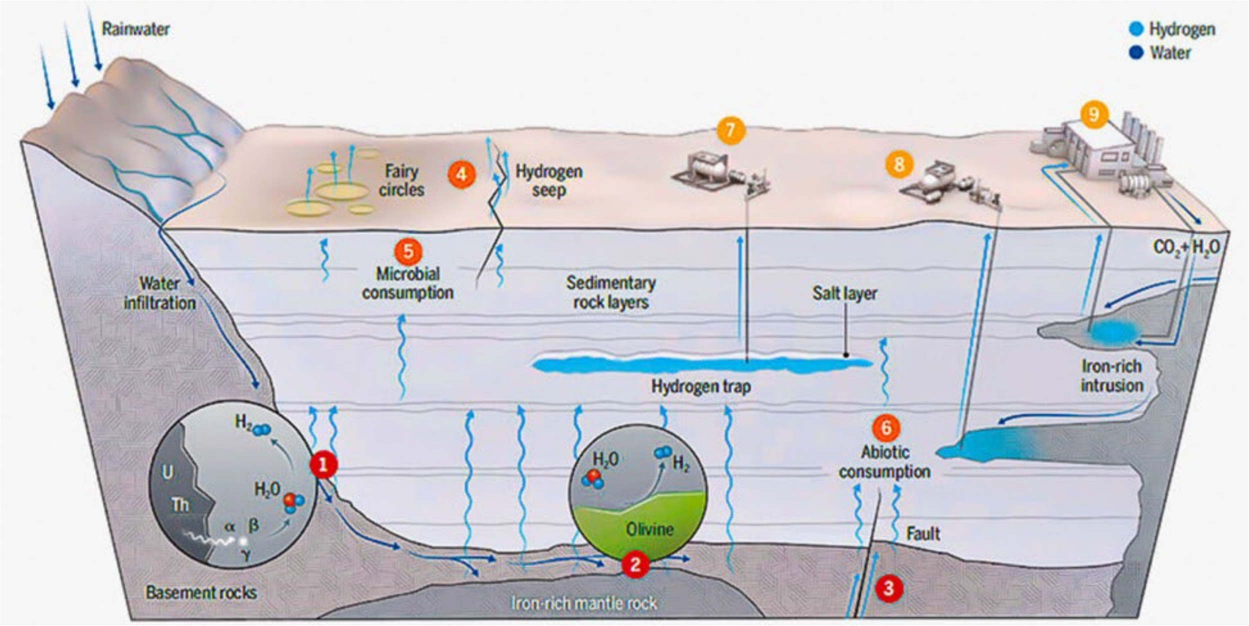
Stimulating white hydrogen

To position itself among the first movers in the emerging white hydrogen space, Granite Creek has teamed up with Cornell University, which recently received a U.S. Department of Energy ARPA-E grant to study the potential geologic hydrogen.

A team led by Greeshma Gadikota, an associate professor who directs the Sustainable Energy and Resource Recovery Group at Cornell, is working with Granite Creek to study the geological hydrogen potential of the Duke Island and Union Bay projects.

"Our team looks forward to this collaboration with Granite Creek on strategies to stimulate geologic hydrogen production, with an emphasis on exploring the ultramafic resources in Alaska," she said.

Stimulated geological hydrogen leverages catalysts found naturally in the ground to speed up Earth's ability to naturally produce hydrogen.



U.S. Geological Survey

Artificial hydrogen is split off water, natural gas, or other sources using catalysts such as PGMs or nickel. This process also occurs naturally in Earth's crust, but usually at a slow rate, and in most cases, the clean-burning fuel escapes too fast to accumulate in economic deposits.

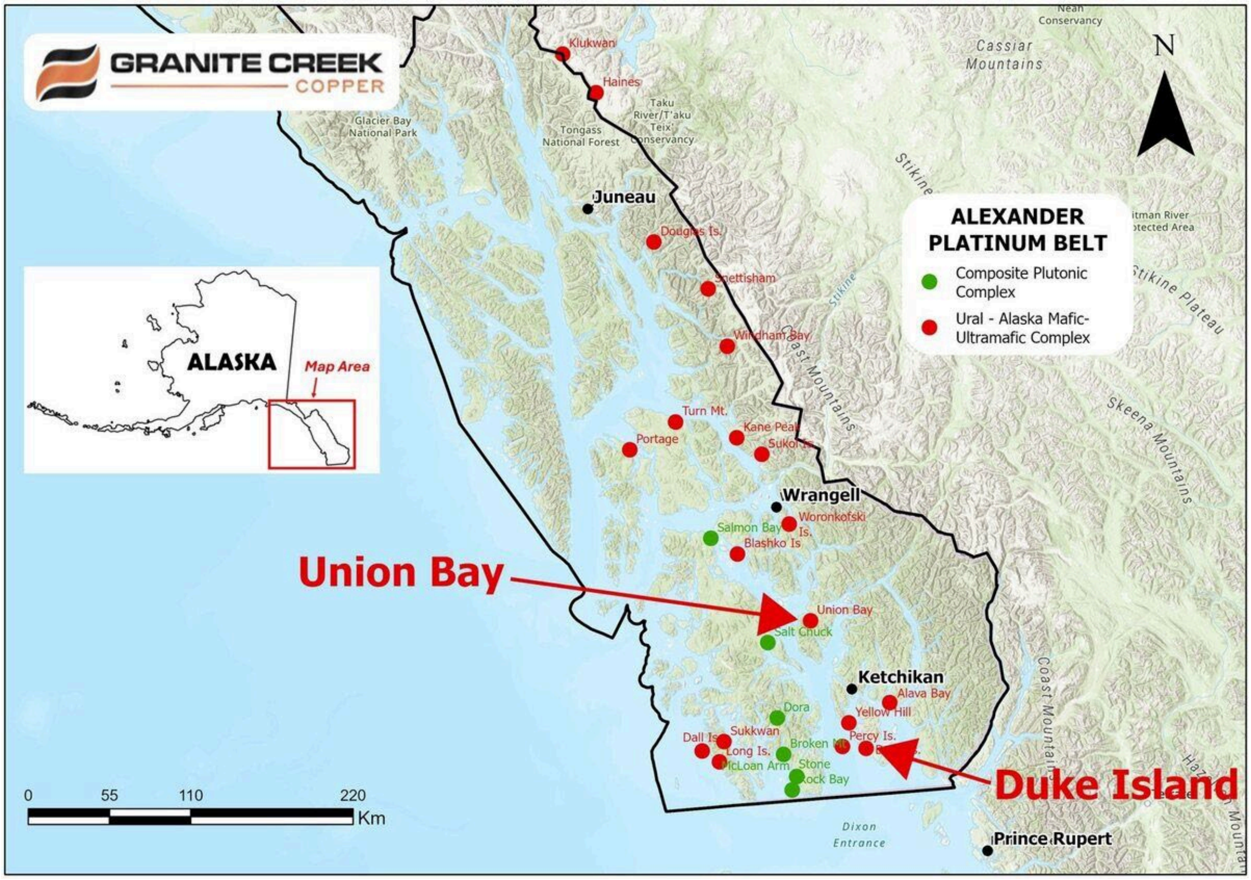
Scientists, however, believe they can generate larger volumes of hydrogen from these rocks by stimulating reactions that would take millions of years to occur naturally.

"Stimulated geologic H2 can decarbonize the supply chain of fuels and can play a major role in the energy transition," said Gadikota. "We see the potential for multi-use approach to these types of projects including critical metal recovery, durable carbon storage, and geologic hydrogen production."

Assembling the pieces

Granite Creek's newly acquired Duke Island and Union Bay projects have the two main ingredients required for white hydrogen – catalysts and water.

"We see the potential for multi-use approach to these types of projects including critical metal recovery, durable carbon storage, and geologic hydrogen production," said Gadikota.



Granite Creek Copper Ltd.

Lying within the Alexander Platinum Belt about 30 miles southeast of Ketchikan, Alaska, Duke Island has long been known for its stores of copper, nickel, and PGMs. Historical exploration on the property has turned up surface samples with grades as high as 1.95% copper, 0.25% nickel, and more than 1 g/t PGMs.

While several prospective zones have been discovered based on geologic mapping, surface geochemistry, and surface and airborne geophysics, only one of these zones has been tested to date with 3,434 meters of drilling in 16 holes. Granite Creek says this drilling has not tested the prospective basal contact of the intrusion where the highest grades of Cu-Ni-PGE sulfide mineralization are inferred to occur.

Granite Creek has entered into an agreement to acquire 90% interest in Duke Island from Stillwater Critical Minerals Inc., which is a fellow company under the Metallic Group of Companies umbrella, for C$150,000 ($108,000) in shares and a commitment to invest at least C$500,000 ($360,000) in exploration over three years. Stillwater will retain a 1% net smelter return on Dukes Island, half of which can be acquired by Granite Creek for C$1 million ($720,000).

Located on an island about 35 miles northwest of Ketchikan, Union Bay hosts classic "Ural-Alaska-type" ultramafic rocks famed for their PGM potential. Mapping, sampling, geophysics, and drilling have identified high-grade platinum targets on this project.

Granite Creek was able to pick up Union Bay by staking 20 mineral claims over the project. "We are very excited to have acquired these projects in Alaska and are proud to collaborate with Dr. Gadikota and her team at Cornell as we add geologic hydrogen to our critical mineral exploration efforts," said Johnson.

Granite Creek's exploration of geological hydrogen in Southeast Alaska follows an announcement earlier this month that it is collaborating with New England Research Inc., a Vermont-based research and development company that recently received a $1.5 million DOE ARPA-E grant, to study geological hydrogen on the company's Star PGM project in Northern B.C.

"We have begun putting the pieces in place, both in terms of projects and global expertise, to position ourselves among the select few first movers in this important new space," the Granite Creek CEO added.

EDITOR'S NOTE: This article was originally published under the headline "Exploring Alaska for geological hydrogen" in the Oct. 30, 2024 edition of Metal Tech News, a Data Mine North publication that delivers the news and insights into technology metals and mining technologies.

SCIENCE ADVANCES | RESEARCH ARTICLE

GEOLOGY

Model predictions of global geologic hydrogen resources

Geoffrey S. Ellis* and Sarah E. Gelman

Geologic hydrogen could be a low-carbon primary energy resource; however, the magnitude of Earth's subsurface endowment has not yet been assessed. Knowledge of the occurrence and behavior of natural hydrogen on Earth has been combined with information from geologic analogs to construct a mass balance model to predict the resource potential. Given the associated uncertainty, stochastic model results predict a wide range of values for the potential in-place hydrogen resource [10^3 to 10^{10} million metric tons (Mt)] with the most probable value of ~5.6×10^6 Mt. Although most of this hydrogen is likely to be impractical to recover, a small fraction (e.g., 1×10^5 Mt) would supply the projected hydrogen needed to reach net-zero carbon emissions for ~200 years. This amount of hydrogen contains more energy (~1.4×10^{16} MJ) than all proven natural gas reserves on Earth (~8.4×10^{15} MJ). Study results demonstrate that further research into understanding the potential for geologic hydrogen resources is merited.

INTRODUCTION

Hydrogen is projected to account for as much as 30% of the future energy supply in some sectors, with the global demand increasing more than fivefold by 2050 (*1*). To achieve net-zero carbon goals, the future supply of hydrogen is expected to be obtained from the electrolysis of water using renewable electricity (also known as green hydrogen) and from fossil fuel sources coupled with carbon capture, utilization, and storage (also known as blue hydrogen) (*2*). However, realization of these production levels will require development of infrastructure at an unprecedented rate (*3*), as well as substantial contributions from technologies that are not commercially viable today (*2*). In addition, hydrogen production may not be as climate friendly as previously assumed (*4*–*6*). Now, hydrogen is generally viewed as a medium for energy storage and transport and not a primary resource (*7*). However, a recent discovery of a substantial accumulation of natural hydrogen in Mali, Africa (*8*–*10*) has challenged the long-held view that such fields do not exist (*11*, *12*). There is a growing recognition among geoscientists that suitable exploration tools have not been deployed in the appropriate locations to truly evaluate the resource potential of natural hydrogen in the Earth's subsurface (*11*–*15*). Information regarding the resource potential of geologic hydrogen can support policy-makers, resource managers, exploration companies, and investors in the decision-making process. However, the uncertainties associated with the generation, migration, accumulation, and preservation of hydrogen in the subsurface make it impossible to precisely determine potential volumes at this time.

A recent compilation of published studies on the global generation of natural hydrogen in all geologic settings estimates the amount to be 15 to 31 million metric tons (Mt or 10^9 g) per year (*16*). Because the global demand for hydrogen is projected to reach ~530 Mt year^{-1} by the year 2050 (*1*), production of all the annually generated hydrogen in the Earth's subsurface would likely represent a small fraction of the needed supply. However, the resource potential for geologic hydrogen is not only dependent on the generation rate but also on the propensity for hydrogen to become trapped in the subsurface and for accumulations to be preserved. Although there is uncertainty related to the presence of hydrogen in the subsurface, much is known about its occurrence and behavior (*16*). Additional inferences can be gained by using knowledge derived from studies of fluid migration, accumulation, and preservation in other fields such as petroleum geology, geothermal energy, and hydrothermal minerals. Information from these studies can be combined to provide some constraints on the possible magnitude of geologic hydrogen resources in the subsurface. We present here a model of the global potential geologic hydrogen resource based on a mass balance approach (Fig. 1). The model results are compared with the projected demand for hydrogen to determine whether natural hydrogen might meet a sufficient portion of the future demand to merit further investigation and exploration. The results can also provide some insight into the most impactful factors affecting the geologic hydrogen resource potential, highlighting the areas that could be a priority for research efforts.

RESULTS

The calculated annual flux of hydrogen from the subsurface to the atmosphere, which is the sum of the nontrapped and leaked hydrogen less the amount consumed by biotic and abiotic processes, was compared to published estimates as a check on our model calculations (Fig. 2). The estimated natural flux to the atmosphere from our model ranges from <1 to ~1×10^3 Mt year^{-1} with the most probable value of ~24 Mt year^{-1} (mean of ~50 Mt year^{-1}). The largest known fluxes of natural hydrogen from the subsurface to the atmosphere are thought to be from volcanic and hydrothermal settings, which are estimated to be ~9.6 ± 7.2 Mt year^{-1} (*17*). The high end of this estimate (16.8 Mt year^{-1}) is similar to the most probable estimated natural flux of hydrogen from the subsurface predicted by our model. Additional contributions of hydrogen to the atmosphere from terrestrial macro- and microseeps are not well constrained and could easily account for a substantial portion of the estimated flux (*16*–*19*). Most (~75%) of the natural flux of hydrogen to the atmosphere is thought to be taken up by soils, but there are large uncertainties associated with the magnitude and mechanisms (*20*). Soils could be consuming a substantially larger amount of hydrogen than

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Energy Resources Program, U.S. Geological Survey, Denver, CO, USA.
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currently estimated or other hydrogen sinks on the Earth's surface may yet be recognized.

The magnitude of the global in-place geologic hydrogen resource today, before anthropogenic production, can be calculated from the mass balance model equations. The calculated total global amount of natural hydrogen in the subsurface ranges from 10^3 to 10^{10} Mt of hydrogen, with the most probable value of ~5.6×10^6 Mt (mean of ~6.8×10^7 Mt) (Fig. 3). Calculated correlation coefficients specify the relative contribution of each of the model inputs on the output distribution. These values indicate that the residence time in reservoirs associated with biological consumption has the largest impact on the predicted geologic hydrogen resource potential, followed by the natural generation rate (Table 1). The magnitude of hydrogen consumption associated with migration and the amount of hydrogen leakage from reservoirs have negligible effects on the predicted resource potential.

DISCUSSION

Given the uncertainties in the model construction and the inputs, the model results should be viewed as a first-order approximation of the magnitude of the potential in-place geologic hydrogen resource. The model makes no predictions about the distribution of the hydrogen in the subsurface, which is critical for the economic viability of any potential resource (*21*). Given what is known about the distribution of petroleum and nonpetroleum fluids (e.g., helium and CO_2) in the subsurface, it is likely that recovery of most subsurface hydrogen can be expected to be in accumulations that are too deep, too far offshore, or too small to be economically recovered. However, if even a small amount of the most probable predicted in-place resource (~5.6×10^6 Mt) was recoverable, this could represent a substantial resource. The global demand for hydrogen is projected to reach ~500 Mt year^{-1} by 2050 (*1*), and recovery of just 2% of the estimated most probable in-place resource would meet the entire

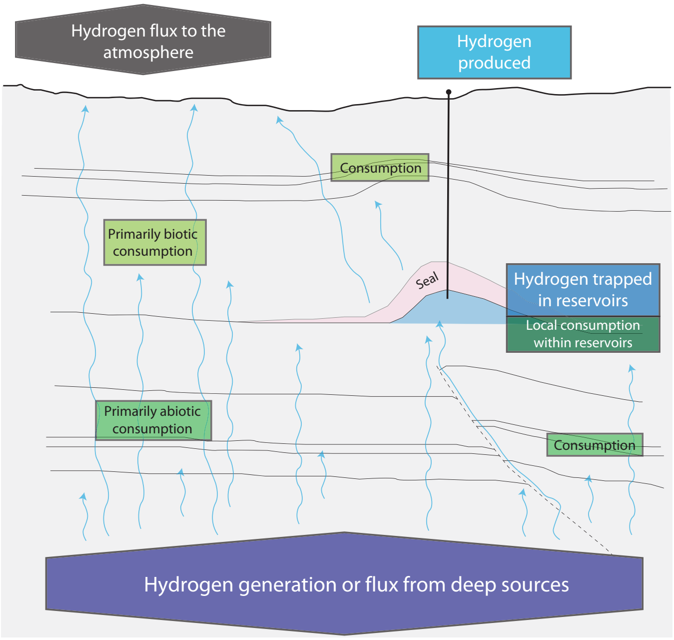

Fig. 1. Conceptual model of geologic hydrogen resources. The model inputs include annual generation of natural hydrogen, fraction of hydrogen detained in traps, residence time in reservoirs, proportion of biotic and abiotic loss, and the rate of anthropogenic production. The calculated outputs of the model are the amount of hydrogen stored in reservoirs at a given time and the flux to the atmosphere.

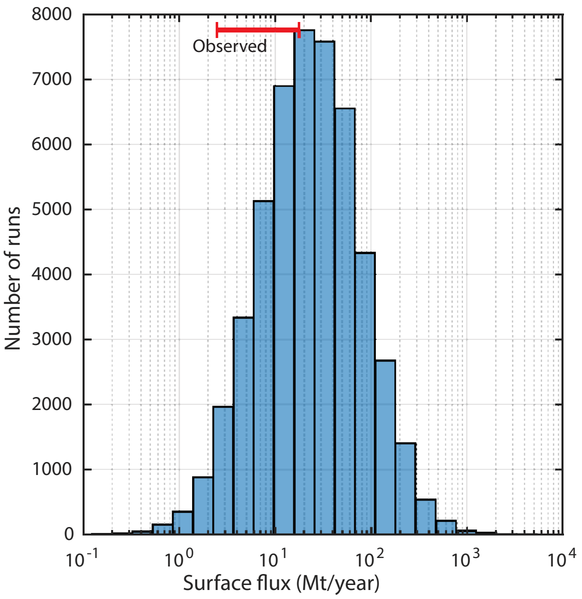

Fig. 2. Estimated annual hydrogen flux to the atmosphere. The sum of the amount of generated hydrogen not trapped or consumed plus the amount that leaks out of reservoirs and is not consumed is considered flux to the atmosphere (blue bars). Volcanic and hydrothermal settings are thought to be the single largest source of hydrogen from the subsurface, contributing ~9.6 ± 7.2 Mt year^{-1} to the atmosphere (red bar) (*17*). Additional contributions of hydrogen to the atmosphere from terrestrial macro- and microseeps are not well constrained (*16*) and could account for the additional predicted flux.

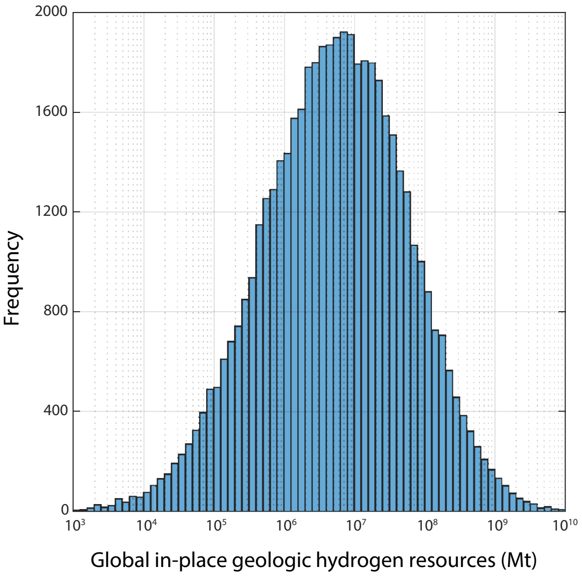

Fig. 3. Distribution of predicted amounts of in-place geologic hydrogen resources. Values range from 10^3 to 10^{10} Mt, with ~5.6×10^6 Mt being the most likely value (P50) and a mean value of ~6.8×10^7 Mt.

Table 1. Model input values and output correlation coefficients. Minimum, maximum, and midpoint values for the input values summarized from literature sources and used in the model calculations. Ranges of input values were normally distributed as shown in fig. S2. Correlation coefficients were calculated with the model outputs.

Input parameter	Min	Mid	Max	Correlation coefficient
H_2 generation (Mt year^{-1})	25	500	25×10^3	0.44
Residence time due to trap leaking (years)	1×10^5	5×10^7	5×10^9	0.09
Residence time due to consumption in reservoir (years)	1×10^4	1.4×10^6	5×10^9	0.72
Trapping efficiency (fraction)	0.001	0.01	0.1	0.30
Consumption (fraction)	0.9	0.95	0.99999	0.0014
Shallow proportion (fraction)	0.9	0.99	0.999	0.016
Deep proportion (fraction)	0.1	0.01	0.001	−0.016

projected global hydrogen demand for ~200 years. Moreover, we calculate the energy content of this estimated recoverable amount of hydrogen (~1×10^5 Mt) to be ~1.4×10^{16} MJ, which is roughly twice the amount of energy in all the proven natural gas reserves on Earth (~8.4×10^{15} MJ).

Our in-place resource estimate is only for natural hydrogen potentially stored in accumulations in the subsurface. It has been suggested that the rate of hydrogen generation may be sufficiently fast such that it could be economically produced from subsurface fluxes without the need for a reservoir, trap, and seal (*14*, *22*). Additionally, it is possible that natural hydrogen production could be stimulated to increase the rate of generation or induce generation in settings where it has the potential but is not naturally doing so (*23*). Although the magnitude of the potential contributions of hydrogen from natural and stimulated generation in real time is currently unconstrained, these contributions could constitute substantial additions to the in-place resource thought to exist in subsurface reservoirs.

Of equal importance to the magnitude of the potential resource is the time that may be required to develop it. A ready supply of low-carbon hydrogen will only make a meaningful contribution toward meeting net-zero carbon emission goals if it can be developed in years or decades rather than centuries (*1*). While the development of petroleum resources has taken over a century to reach maturity, there is a good reason to believe that natural hydrogen resources can be developed much more quickly. Although not a perfect analog, the experience of US shale gas resource development suggests that geologic hydrogen could begin to make a substantial contribution to the global energy supply within decades (*24*). Our model predicts that geologic hydrogen production rates could provide half of the projected supply of blue hydrogen by the end of this century, which would substantially reduce the necessary capacity for carbon capture, utilization, and storage (Fig. 4). The rate of progress toward realizing potential geologic hydrogen resources will depend, in large part, on the level of investment in the development of exploration and production strategies and associated technologies. Furthermore, there is a ~94% probability that the subsurface endowment of natural hydrogen will exceed future extraction capacity through the year 2100 and a >75% probability of this being the case beyond the year 2200.

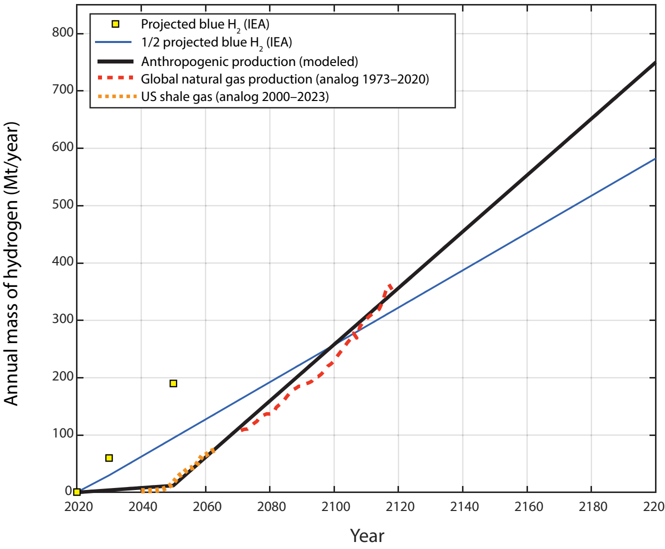

Fig. 4. Model and analog trends utilized for modeling future anthropogenic production of hydrogen. The bold black curve corresponds to the modeled annual production of H_2 implemented in this study. For comparison, the solid blue curve illustrates a continuous trend for half of projected blue hydrogen production based on the International Energy Agency (IEA) estimates (yellow squares) (*1*). Analogs from historical natural gas production are converted from produced natural gas volumes to mass of hydrogen, for both US shale gas (*24*) and global natural gas (*71*).

Several recent studies have claimed that natural hydrogen generation rates are rapid enough to potentially offset anthropogenic extraction rates from reservoirs, thereby constituting a renewable resource (*8*, *9*, *14*). Using our hydrogen production model based on historical natural gas production, the most probable (P50) global renewable hydrogen production rate is estimated to be about 5 Mt year^{-1} (P90 = 1 Mt; P10 = 29 Mt) (Fig. 5), which would meet <1% of the projected worldwide demand for hydrogen in 2050 (*1*). Slower hydrogen extraction rates could increase the amount of renewable resource produced annually but would reduce the contribution that natural hydrogen would have toward decarbonizing the energy supply. However, our model does not account for potential geologic hydrogen that might be produced as it is generated or moves through

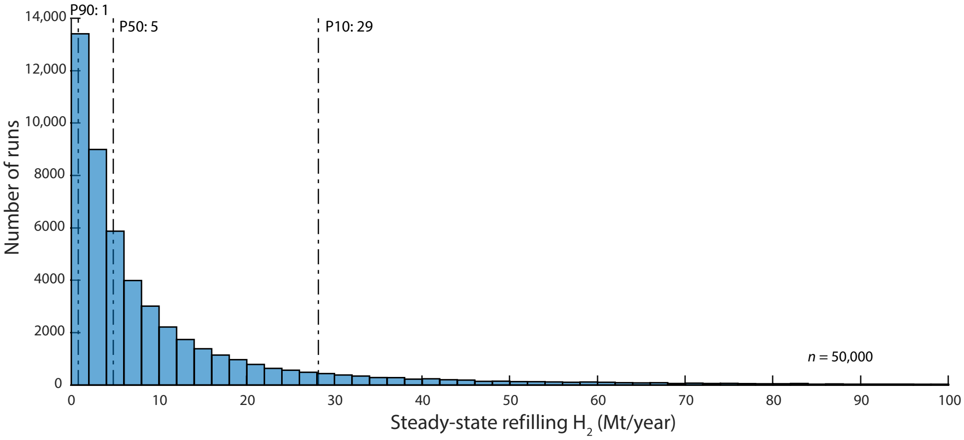

Fig. 5. Predicted renewable geologic hydrogen potential. Results of the steady-state refilling (newly generated, migrated, and trapped) hydrogen termed "renewable" hydrogen.

the subsurface, which would be a renewable resource. This form of geologic hydrogen production is totally hypothetical, and the magnitude of this resource cannot currently be estimated.

Our model provides an initial framework for assessment of the global resource potential of natural hydrogen. The estimated amount of in-place hydrogen in the Earth's subsurface is highly uncertain, varying over seven orders of magnitude; however, the predicted flux to the atmosphere is less variable (three orders of magnitude), with the most probable value roughly within a factor of 2 of current observations. The approach can be improved as more knowledge is acquired and would benefit from geographic and stratigraphic constraints. The study results indicate that a substantial hydrogen resource could exist in the subsurface of Earth, the magnitude of which, if proven, could substantially contribute to the decarbonization of energy resources but is not likely to be renewable. These findings indicate that further research in this field is warranted. A better understanding of the rates and controls on geologic hydrogen consumption in subsurface accumulations and more accurate estimates of the rates of natural hydrogen generation would improve model predictions of the resource potential. Realization of potential natural hydrogen resources will require a more advanced understanding of the processes that lead to the accumulation of hydrogen in the subsurface as well as optimized methods for finding these resources.

MATERIALS AND METHODS

Derivation of mass balance model equation

To constrain the estimated subsurface resource potential of geologic hydrogen, we have taken a simple mass balance approach describing the expected sources and sinks of naturally occurring hydrogen in the Earth's crust (fig. S1). The flux of geologic hydrogen generation in the deep subsurface is considered the main source of hydrogen to the model. The main geologic sink is biotic or abiotic consumption. Hydrogen that is generated geologically either can be trapped in a subsurface reservoir or is never trapped and leaks directly to the surface. In the former case, we consider that hydrogen may be consumed in the reservoir and that traps may leak over geologic timescales. Here, we derive the mass balance equations of the model as shown schematically in the Supplementary Materials (fig. S1); a summary of nomenclature is provided in table S1.

We define the geologic generative flux of hydrogen in the subsurface as $\frac{\partial M_P}{\partial t}$, which is equal to the surface flux of hydrogen, $\frac{\partial M_S}{\partial t}$, plus the flux of hydrogen that is consumed either biologically or abiotically in the subsurface, $\frac{\partial M_B}{\partial t}$

$$\frac{\partial M_P}{\partial t} = \frac{\partial M_S}{\partial t} + \frac{\partial M_B}{\partial t} \tag{1}$$

This surface flux is composed of hydrogen that was generated and either never trapped in a subsurface reservoir ("never trapped") or trapped and subsequently leaked over geologic time ("leaked"). Hydrogen that was trapped but never leaks would not migrate to the surface and thus would not be included in the surface flux. Biologic or abiotic consumption reduces the amount of hydrogen that was generated along both routes to the surface. To characterize the proportion of hydrogen that is generated and trapped, we define the trapping efficiency, ϵ.

The portion of the surface flux that was never trapped (and remains after biotic/abiotic consumption) is

$$\left(\frac{\partial M_S}{\partial t}\right)_{NT} = (1-\epsilon)\left(1-f_B\right)\frac{\partial M_P}{\partial t} \tag{2}$$

The portion of the surface flux that was trapped but leaked requires a rate at which hydrogen leaks from reservoirs in the subsurface, denoted $\frac{\partial M_L}{\partial t}$. For simplicity, we consider this as a time-dependent decay process, wherein a decay constant, λ, describes the half-life of trapped hydrogen, the residence time is denoted τ, and the mass of the hydrogen trapped in reservoirs at any moment in time is M_R

$$\frac{\partial M_L}{\partial t} = \lambda_L M_R = \frac{M_R}{\tau_L} \tag{3}$$

Next, the rates of biotic and abiotic consumption must be defined. We consider four terms to capture these processes: (i) consumption that occurs during migration, focused on hydrogen that is never trapped in reservoirs; (ii) consumption that occurs during migration, focused on hydrogen migrating in the deep subsurface at high temperature and likely before trapping; (iii) consumption that occurs during migration, focused on hydrogen migrating in the shallow subsurface at low temperature and likely occurring to hydrogen after it has leaked from traps; and (iv) consumption that occurs locally within reservoirs. Further explanation on the efficiency of deep (likely dominated by abiotic processes) versus shallow consumption (likely dominated by biotic processes) is provided in the "Biotic and abiotic loss" section.

For simplicity, we consider the consumption of hydrogen occurring during migration to be proportional in magnitude to the overall generative flux of hydrogen, where f_B denotes the proportion of hydrogen that is consumed along migration pathways

$$\frac{\partial M_B}{\partial t} = f_B \frac{\partial M_P}{\partial t} \tag{4}$$

We further assume biotic/abiotic consumption during migration to be more efficient in the shallow subsurface at low temperature; thus, a higher proportion of hydrogen is likely to be consumed after hydrogen has leaked from reservoirs in route to the surface, while a lower proportion may be consumed before hydrogen being trapped in reservoirs. We define a parameter, x, as the proportion of consumption that occurs in the shallow subsurface. Last, the portion of surface flux that was leaked (and remains after biotic/abiotic consumption) is

$$\left(\frac{\partial M_S}{\partial t}\right)_L = \left(1-f_B\right)^x \frac{\partial M_L}{\partial t} = \left(1-f_B\right)^x \frac{M_R}{\tau_L} \tag{5}$$

The total surface flux of both never trapped and leaked hydrogen is obtained by combining Eqs. 2 and 5

$$\frac{\partial M_S}{\partial t} = \left(\frac{\partial M_S}{\partial t}\right)_{NT} + \left(\frac{\partial M_S}{\partial t}\right)_L = (1-\epsilon)\left(1-f_B\right)\frac{\partial M_P}{\partial t} + \left(1-f_B\right)^x \frac{M_R}{\tau_L} \tag{6}$$

To define the hydrogen loss term in Eq. 1, we must consider the multiple sinks outlined above associated with consumption, following the terms defined in fig. S1. The hydrogen that was never trapped but consumed during migration is

$$\left(\frac{\partial M_B}{\partial t}\right)_{NT} = (1-\epsilon) f_B \frac{\partial M_P}{\partial t} \tag{7}$$

The hydrogen that is consumed at depth before being trapped in reservoirs is

$$\left(\frac{\partial M_B}{\partial t}\right)_{PTD} = \epsilon\left[1-\left(1-f_B\right)^{1-x}\right]\frac{\partial M_P}{\partial t} \tag{8}$$

The hydrogen that is consumed at shallow depths after being leaked from reservoirs is

$$\left(\frac{\partial M_B}{\partial t}\right)_{PTS} = \left[1-\left(1-f_B\right)^x\right]\frac{M_R}{\tau_L} \tag{9}$$

Although stored within reservoirs, we also consider the loss of hydrogen to local biotic consumption. This process is also modeled as a time-dependent decay process. We consider the change in the mass of hydrogen in the reservoir due to local consumption to be

$$\left(\frac{\partial M_B}{\partial t}\right)_R = \lambda_C M_R = \frac{M_R}{\tau_C} \tag{10}$$

The total sum of all terms relating to consumption therefore is

$$\frac{\partial M_B}{\partial t} = \left(\frac{\partial M_B}{\partial t}\right)_{NT} + \left(\frac{\partial M_B}{\partial t}\right)_{PTD} + \left(\frac{\partial M_B}{\partial t}\right)_{PTS} + \left(\frac{\partial M_B}{\partial t}\right)_R \tag{11}$$

We can relate this total surface flux and the total consumption-associated losses back to the total mass balance, combining Eqs. 1, 6, 11 and simplifying

$$\frac{\partial M_P}{\partial t} = (1-\epsilon)\left(1-f_B\right)\frac{\partial M_P}{\partial t} + \left(1-f_B\right)^x\frac{M_R}{\tau_L} + (1-\epsilon)f_B\frac{\partial M_P}{\partial t} + \epsilon\left[1-\left(1-f_B\right)^{1-x}\right]\frac{\partial M_P}{\partial t} + \left[1-\left(1-f_B\right)^x\right]\frac{M_R}{\tau_L} + \frac{M_R}{\tau_C}$$

Expanding parenthesis

$$\frac{\partial M_P}{\partial t} = \left[1-f_B-\epsilon+\epsilon f_B\right]\frac{\partial M_P}{\partial t} + \left(1-f_B\right)^x\frac{M_R}{\tau_L} + \left(f_B-\epsilon f_B\right)\frac{\partial M_P}{\partial t} + \left[\epsilon-\epsilon\left(1-f_B\right)^{1-x}\right]\frac{\partial M_P}{\partial t} + \frac{M_R}{\tau_L} - \left(1-f_B\right)^x\frac{M_R}{\tau_L} + \frac{M_R}{\tau_C}$$

Removing cancelled terms

$$\frac{\partial M_P}{\partial t} = \frac{\partial M_P}{\partial t} + \left(1-f_B\right)^x\frac{M_R}{\tau_L} - \epsilon\left(1-f_B\right)^{1-x}\frac{\partial M_P}{\partial t} + \frac{M_R}{\tau_L} - \left(1-f_B\right)^x\frac{M_R}{\tau_L} + \frac{M_R}{\tau_C}$$

Removing another set of cancelled terms

$$0 = -\epsilon\left(1-f_B\right)^{1-x}\frac{\partial M_P}{\partial t} + \frac{M_R}{\tau_L} + \frac{M_R}{\tau_C}$$

Rearranging and solving for M_R

$$\epsilon\left(1-f_B\right)^{1-x}\frac{\partial M_P}{\partial t} = \frac{M_R}{\tau_L} + \frac{M_R}{\tau_C}$$

$$\frac{\epsilon\left(1-f_B\right)^{(1-x)}}{\frac{1}{\tau_L}+\frac{1}{\tau_C}}\frac{\partial M_P}{\partial t} = M_R \tag{12}$$

Equation 12 thus provides an analytical solution for the mass of trapped hydrogen in the subsurface (M_R) before human exploration (steady state; Fig. 3).

Anthropogenic exploration and production of hydrogen would disrupt the steady-state solution obtained in Eq. 12. This requires the incorporation of transient losses of trapped hydrogen due to resource exploitation and the counterbalancing effect of refilling of these traps due to continued hydrogen migration from deep generation. Thus, we seek to obtain a function for the change in mass of trapped hydrogen with time, $\frac{\partial M_R}{\partial t}$. Before any human exploration, this flux of trapped hydrogen depends only on the flux of hydrogen leaking from the traps, $\frac{\partial M_L}{\partial t}$, and a term describing the refilling of deep, geologically produced hydrogen denoted by $\frac{\partial M_F}{\partial t}$

$$\frac{\partial M_R}{\partial t} = \frac{\partial M_F}{\partial t} - \frac{\partial M_L}{\partial t} \tag{13}$$

Using the terms in fig. S1 for $\frac{\partial M_F}{\partial t}$, the mass balance equation for the change in trapped hydrogen with time is

$$\frac{\partial M_R}{\partial t} = \epsilon\left(1-f_B\right)^{(1-x)}\frac{\partial M_P}{\partial t} - \frac{M_R}{\tau_L} - \frac{M_R}{\tau_C} \tag{14}$$

Last, an additional term can be added to capture anthropogenic production, giving the master mass balance equation used for this study

$$\frac{\partial M_R}{\partial t} = \epsilon\left(1-f_B\right)^{(1-x)}\frac{\partial M_P}{\partial t} - \frac{M_R}{\tau} - \frac{M_R}{\tau_C} - \frac{\partial M_D}{\partial t} \tag{15}$$

This can be checked with the global mass balance equations above. In the steady state, $\frac{\partial M_R}{\partial t} = 0$ and $\frac{\partial M_D}{\partial t} = 0$. This reduces to

$$0 = \epsilon\left(1-f_B\right)^{(1-x)}\frac{\partial M_P}{\partial t} - \frac{M_R}{\tau} - \frac{M_R}{\tau_C} \tag{16}$$

which is equivalent to Eq. 12.

Numerical modeling methodology

The mass of trapped hydrogen in the subsurface through time is described by Eq. 14. This is an ordinary differential equation and was solved using a fourth-order Runge-Kutta algorithm (*25*). A MATLAB (MathWorks, Natick, MA) routine was created with the following broad steps:

1) Define input distributions for ϵ, f_B, x, τ, and $\frac{\partial M_P}{\partial t}$. These are shown in fig. S2 and described in the main text (Table 1).

2) Define the anthropogenic production trend, shown in Fig. 4.

3) In a parallel "for loop," run a Monte Carlo simulation (50,000 runs) that solves Eq. 14 using the Runge-Kutta algorithm.

4) Postprocess results.

All MATLAB scripts used to calculate the model outputs are available in the Supplementary Materials.

Estimation of input ranges

The conceptual model contains inputs that include the annual generation of natural hydrogen, the fraction of hydrogen that can be detained in traps, the residence time in reservoirs, the proportion of hydrogen lost through biotic and abiotic processes, and the rate of withdrawal associated with anthropogenic exploitation (Fig. 1). Given the extensive uncertainty associated with hydrogen generation rates, trapping efficiency, and residence times, these inputs were represented with normal distributions on a logarithmic scale (fig. S2). This produces a log-normal distribution on a linear scale, with preferential sampling focused on the low end. The loss of hydrogen and the rate of hypothetical anthropogenic production are better constrained and represented by a linear distribution (fig. S2) and analog production curve (Fig. 4), respectively. The model is assumed to be at steady state with respect to the hydrogen flux before anthropogenic withdrawals from reservoirs. Ranges of input values into the model, as derived from studies of natural hydrogen occurrences and geologic analogs, are described below and summarized in Table 1. The calculated outputs of the model are the amount of hydrogen stored in reservoirs at a given time and the flux to the atmosphere.

Natural hydrogen generation

The scarcity of native hydrogen associated with hydrocarbon gases has fostered a persistent perception that it does not occur on Earth (*12*). More than 30 natural processes capable of generating hydrogen have been identified, although most are thought to produce small amounts (*26*). A recent review of the occurrence of natural hydrogen on Earth estimated the annual global production from geologic environments to be 23 ± 8 Mt year^{-1} (*16*). This estimate is based on a limited number of laboratory experiments and field observations that have been extrapolated to the global scale. Several lines of reasoning support the notion that the current estimate of annual hydrogen generation in geologic settings is a minimum value. Geologic settings that are capable of generating the largest amounts of hydrogen are underexplored for gas resources, and accidental discoveries are often unreported (*27*). The earliest published estimate of global geologic hydrogen production, in 1983, was a mere 0.027 Mt year^{-1} (*28*), and every subsequent study has predicted an increased amount typically by an order of magnitude or more (*16*, *29*–*31*). Historically, subsequent observations of fluxes of hydrogen from the subsurface, which can be a proxy for generation rate in some settings, have frequently recorded larger volumes than previously detected. For example, a recent discovery in a chromite mine in Albania measured an annual flux of hydrogen more than two orders of magnitude greater than any previous observation from an ophiolite setting (0.3667 versus 0.0018 ton m^{-2} year^{-1}) (*32*). Areas of microseepage of hydrogen also provide some additional evidence for the magnitude of annual hydrogen generation in local areas. For example, hydrogen flux to the atmosphere at one site in Russia was found to be ~0.25 ± 0.03 Mt year^{-1} km^{-2} (*18*) and ~1.15 ± 0.15 Mt year^{-1} km^{-2} was recorded at a site in Brazil (*19*). Estimates of hydrogen flux from these two sites alone are equivalent to ~15% of the total flux from all known volcanic and hydrothermal settings (*17*). It is important to note that translation of surface flux measurements to deep subsurface generation rates is complicated by the potential for near-surface hydrogen generation (*33*) and uncertainties in diffusion models (*34*), as well as the potential for substantial consumption of hydrogen by biotic and abiotic processes along migration pathways (*35*–*37*) (see the "Biotic and abiotic loss" section). This leads to the reasonable inference that observed fluxes of hydrogen in the near subsurface are likely reflective of much larger subsurface generation rates. Additionally, nearly all published measurements of hydrogen flux have been short term (minutes to hours). Limited time-series observations of hydrogen flux have shown that it can be highly sporadic, demonstrating that instantaneous measurements may not capture the maximum flux [see, for example, (*19*)]. Furthermore, the published values for rates of hydrogen generation in the subsurface are generally conservative minimal values (*38*).

Additionally, recent studies indicate that hydrogen generation is associated with more lithologies and under wider environmental conditions than previously recognized. For example, serpentinization-type reactions involving the reduction of water by iron-rich minerals have generally been regarded as requiring high temperatures (>~200°C) (*39*). However, there is growing evidence that these reactions can take place at much lower temperature conditions (<<200°C) [see, for example, (*40*) and references therein], which suggests that a much larger volume of rock is likely capable of generating hydrogen via serpentinization reactions than is accounted for in current estimates of annual global generation. Furthermore, other lithologies not previously accounted for in global generation estimates have recently been proposed as candidates for generation of substantial amounts of hydrogen including the reduction of water by iron-rich minerals in banded iron formations (*41*, *42*) and high–thermal maturity organic-rich rocks (*43*, *44*). Mahlstedt *et al.* (*44*) estimate that the overmature (i.e., beyond hydrocarbon generation) Patchawarra Formation in the Cooper Basin in Australia may contain a concentration of molecular hydrogen that is twice the natural gas concentration of the prolific Barnett Shale in Texas, United States.

A major uncertainty is the potential flux of hydrogen from deep crustal faults that may be conduits for fluids upwelling from the mantle. Although the upper mantle is largely oxic with H–C–O existing as CO_2 and H_2O in shallow regions, mantle heterogeneity and nonideal mixing provide potential for a high degree of variability in the fO_2 (oxygen fugacity) of the mantle (*45*). Theoretical calculations indicate that at pressures >3 GPa (~100 km depth), CH_4, H_2O, and H_2 are stable, with H_2 constituting ~0.05 mole fraction of the fluid (*46*). The upper mantle is estimated to contain 0.04 of the Earth's surface ocean mass of water (*47*), which could equate to ~300×10^6 Mt of H_2. Numerous experimental studies demonstrate the potential for H_2 generation and stability under mantle conditions (*48*–*54*). Additionally, there is evidence for hydrogen-rich gas from the solar nebula to have been incorporated into Earth during early planetary accretion. Hydrodynamic escape is thought to have resulted in early loss of large amounts of nebular volatiles such as hydrogen (*55*), yet noble gas and stable isotopic geochemical data support the notion that the current endowment of hydrogen on Earth was derived from a mixture of primordial and accreted (chondritic) hydrogen (*56*–*60*). Last, theoretical models (*61*–*63*) and experimental studies (*22*, *64*–*67*) have shown that large amounts of hydrogen may be incorporated into the Earth's core as metal hydrides or H_2O. It has been estimated that the core could contain as much as five ocean volumes of water (*62*). The amount of H_2 generated or stored in the mantle and core that could be transported to the crust is completely unconstrained. Noble gases are known to reach the crust from the mantle (*55*) and even the core (*68*); however, H_2 is highly reactive and susceptible to redox conditions, so preservation throughout migration is a risk. Nonetheless, the magnitude of the reservoir of hydrogen in the deep interior of Earth is likely to be quite large and even a small fraction that escapes to the crust could constitute a substantial source for crustal accumulations.

For these reasons, we assume that the current estimate of annual hydrogen generation in geologic settings [23 ± 8 Mt $year^{-1}$ (*16*)] is a minimum value and that the actual value may be up to three orders of magnitude larger. Consequently, we set the maximum generation rate at 25,000 Mt $year^{-1}$. We also infer that the mean value for annual hydrogen generation is likely to be much closer to the current estimate given that the maximum generation rate likely requires a substantial contribution from a deep hydrogen source (i.e., mantle and core), which is highly uncertain. The model uses 500 and 25 Mt $year^{-1}$ for the median and minimum input values, respectively (Table 1 and fig. S2). Sensitivity tests exploring the impact of the highly uncertain maximum generation rate value show that model results are relatively insensitive to this number, with rates of 2500, 25,000, and 250,000 Mt $year^{-1}$ all still resulting in a median (P50) subsurface hydrogen resource estimate of ~5.6×10^6 Mt.

Fraction trapped

Some fraction of the total volume of hydrogen moving through the subsurface will migrate into geologic traps, and the balance will escape toward the surface, which is referred to as the trapping efficiency. Trapping efficiency has been studied in petroleum systems and found to be highly variable, with amounts trapped in individual catchments ranging from 0 to 66% of the amount generated (*69*). The maximum trapping efficiency for an entire petroleum system has been estimated to be as high as ~35% (*70*, *71*); however, other authors have suggested that the maximum is more likely to be closer to ~10%, with average values of a few percent being the most common (*72*, *73*). On the basis of a comprehensive study of 16 petroleum systems from around the world, Magoon and Valin (*70*) classified petroleum systems as very efficient (>10%), moderately efficient (1 to 10%), and inefficient (<1%). Given the possibility that hydrogen trapping may be less efficient than petroleum, input values for our model ranging from 0.1 to 10% are taken to be a conservative estimate of hydrogen trapping efficiency (Table 1 and fig. S2).

Physical losses from reservoirs

Trapped hydrogen may escape over time due to leakage through reservoir seals, and the flux of hydrogen out of reservoirs can be accounted for by a residence time in the reservoir. Although the small size of hydrogen atoms has led to speculation that molecular hydrogen easily diffuses through most materials (*16*), there is evidence for a natural gas accumulation in Australia containing ~11% hydrogen having been preserved for millions of years (*74*). The kinetic diameter of molecular hydrogen (H_2) is similar to that of a helium atom (*75*), and the diffusivities of these species through natural materials are similar (*76*). Low-permeability seals, such as evaporites and carbonates, allow natural helium accumulations to be trapped for long periods of time [>100 million years (Myr)] without notable diffusive leakage (*77*–*79*). Additionally, the capillary entry pressure required to force helium gas through seal rocks is similar to that of CO_2 (*80*), suggesting that natural CO_2 accumulations are also appropriate analogs for gas-phase hydrogen resources. CO_2 accumulations have been shown to be in place for >100 Myr (*81*). In addition to diffusive loss, hydrogen loss may occur through advective processes. The residence time for hydrogen-filled reservoirs with advective gas loss through leaky seals was estimated to be 1×10^4 years in one recent model of natural hydrogen accumulation (*82*). The model input range for the residence time associated with leakage of hydrogen trapped in reservoirs is taken to be 1×10^5 years to 5 billion years (Gyr) (Table 1 and fig. S2).

Biotic and abiotic loss

The loss of hydrogen through biologic and abiotic processes is captured in the consumption terms of the model, which have been broken down into three components to account for the complex and potentially substantial role of consumption of hydrogen in the subsurface. Two components of the model focus on consumption that may occur while hydrogen is migrating through the subsurface, whereas the third component treats consumption that may occur while hydrogen is stored within reservoirs. The treatment of consumption of hydrogen during migration is considered for both deep or high-temperature regions (driven by abiotic consumption) versus shallow or low-temperature regions (driven by biotic consumption). The most widely recognized mechanisms for abiotic destruction of H_2 in nature involve the catalytic hydrogenation of CO or CO_2 at elevated temperatures (*83*), which is analogous to engineered hydrocarbon synthesis processes involving metallic iron and nickel known as Fischer-Tropsch and Sabatier synthesis, respectively (*84*). However, the prevalence of effective catalysts (e.g., Fe-Ni alloys) in natural environments has been questioned (*85*), and if they are present, the operative ranges of temperature and water-to-rock ratios are thought to be quite narrow (*39*). Furthermore, sustained catalytic reactions require a high surface area of the metal (to maximize reactive sites), low sulfur concentrations (to avoid catalyst poisoning), and low hydrogen-to-carbon ratios (to reduce coke deposition) (*86*). These conditions can be controlled in laboratory and industrial settings but are likely to be rare in natural environments (*85*). Thus, the model assumes that hydrogen consumption at greater depth (i.e., higher temperatures) is much less efficient than hydrogen consumption in shallower cooler settings where microbial processes are most effective (<120°C) (*87*). Deep hydrogen consumption during migration is estimated to constitute from 0.1 to 10% of the total hydrogen consumption (Table 1 and fig. S2).

There is a growing recognition that substantial microbial communities capable of utilizing and producing hydrogen exist in the subsurface (*35*), yet studies of the magnitude of subsurface microbial hydrogen consumption are limited and restricted to a few geologic settings. One study of the Juan de Fuca Ridge in the eastern Pacific Ocean found that microbes consume ~50 to 80% of the locally produced hydrogen (*88*), and another on the Mid-Atlantic Ridge estimated hydrogen consumption approaching approximately 90% of the production (*89*). A global model of hydrogen sources and sinks at mid-ocean ridges conservatively estimates the minimum amount of microbial consumption in these settings to be ~30% of the produced hydrogen (*90*). A case study based on laboratory incubations of soils from the São Francisco Basin in Brazil predicted a 40% reduction in hydrogen concentration in the upper 1 m of soil and noted that the observed rate was three to four orders of magnitude lower than previous studies of low-affinity hydrogen consumers (*91*). Recent work on the Samail ophiolite in Oman has observed active hydrogenotrophy capable of reducing aqueous hydrogen concentrations by six orders of magnitude over just a few hundreds of meters depth range (*92*, *93*). Paradoxically, the known hydrogen accumulation in Mali contains nearly pure hydrogen gas in a reservoir that is only a few hundred meters deep (*9*), highlighting the importance of other environmental factors (e.g., aqueous media and nutrient availability) in controlling the rate of microbial hydrogen consumption (*35*). Although not strictly consumption, the sorption of hydrogen on clay minerals is another potential mechanism for loss of hydrogen at lower temperatures (*94*). The total hydrogen consumption from combined deep (primarily abiotic) and shallow (primarily biologic) migration is assumed to range from 90 to 99.999% in the model (Table 1 and fig. S2).

Microbial consumption of fluids stored in reservoirs at low temperature (<80°C) is a well-established phenomenon in petroleum geology, wherein long-chain hydrocarbons are consumed as methane is produced (*95*). An analogous loss of hydrogen while stored in shallow, low-temperature reservoirs is likely to also occur and is represented here with a second residence time. Because biodegradation rates are poorly constrained, even in petroleum systems, the estimated rate from Larter *et al.* (*95*) of 10^{-3} to 10^{-4} kg petroleum m^{-2} $year^{-1}$ is used, following a methodology similar to that used by Prinzhofer and Cacas-Stentz (*82*). Taking the mid-range of this estimate and using a petroleum density of 700 kg m^{-3}, the mid-case residence time is calculated to be 1.4×10^6 $year^{-1}$. Although far more rapid rates for biological consumption of hydrogen have been reported in soils [as rapid as weeks (*91*)], reservoirs, traps, and especially seals of subsurface fluid accumulations are only likely in bedrock layers underlying soil. Many traps are likely to be at greater depth with temperatures >100°C, precluding a major role for microbial activity within the reservoir (*95*). Thus, the model input range for the residence time associated with in-reservoir consumption is taken to be 1×10^4 years to 5 Gyr (Table 1 and fig. S2).

Anthropogenic hydrogen production potential

Similar to early exploration efforts for other commodities, exploration for geologic hydrogen will likely proceed slowly at first since new concepts for the geologic hydrogen system and prospect definition are still being developed (*96*). However, as this system is better understood through research, development, and prospect testing, production of geologic hydrogen will likely accelerate. Extraction of potential hydrogen gas resources is modeled on historical natural gas production and is referred to as exploration/production efficiency. US shale gas production is taken as an analog for early hydrogen development (*24*). Admittedly, there are notable differences between development of shale gas and natural hydrogen resources. In the case of shale gas, the location of the resource was well known, and successful production was dependent on the development of efficient engineering solutions to extract it. In contrast, the location of potential hydrogen accumulations is unknown, yet once located they are likely to be producible with technologies similar to those used for natural gas. Nonetheless, it can reasonably be assumed that there will be a period of low initial hydrogen production, as was experienced in shale gas development, that reflects the learning curve of the evolution of exploration strategies.

Model values for the later more mature phase of hydrogen production are based on the global natural gas production from 1973 to 2020 (*97*). Both the US shale gas and global natural gas production datasets were converted from cubic feet of natural gas to cubic feet of hydrogen and then to million metric tons of hydrogen. We used a piecewise linear curve to represent this probable production history. From 2020 to 2050, we follow the ramp-up of US shale gas (we assume that some shale gas production began as early as 1980 and then follow the available data trend from 2000 to 2023), whereas from 2050 to 2200, we follow the approximately linear increase in gas production globally (analog data from 1973 to 2020). This production curve is initiated at 2020 in the model, and the final piecewise linear curve is shown in Fig. 4.

The percent of in-place resource recoverable (i.e., recovery factor) for oil is thought to be approximately 30 to 35% (*98*) but is substantially higher for natural gas accumulations, typically ~50 to 80% (*99*). To account for the likelihood of subeconomic hydrogen accumulations (i.e., too small, too deep, and too far offshore), exploration inefficiency (i.e., inability to locate economic accumulations), and a 50 to 80% recovery factor, the maximum production amount is capped at 10% of subsurface reservoir amount.

Predicted trends for future demand and production of hydrogen provide some insight into the potential for geologic hydrogen to meet the future demand. To provide a baseline on possible demand for geologic hydrogen, a comparison was drawn from blue hydrogen. The International Energy Agency (IEA) projection of the supply of blue hydrogen over the coming decades needed to reach net-zero carbon emission goals is used as a reference case (*1*). The IEA projections for total supply of hydrogen-based fuels in 2020, 2030, and 2050 are 87, 212, and 528 Mt, respectively (*1*), and the projections for the role of blue generation in the same years are 0.7, 28, and 36% of the total. Thus, the total production of blue hydrogen is projected to be 0.63, 60, and 190 Mt (for 2020, 2030, and 2050, respectively). To set realistic amounts for a new technology such as geologic hydrogen exploration, we divided these values in half as a desirable benchmark for future demand. Comparison of the model of geologic hydrogen production with the reference case is shown in Fig. 4.

Using the model inputs specified in Table 1 and fig. S2, potential subsurface hydrogen resource estimates range from 10^3 to 10^{10} Mt, with the most likely value of ~5.6×10^6 Mt (Fig. 3). Meanwhile, the estimated future annual demand beyond 2100 may be several hundred million metric tons (Fig. 4). Although the in-place resource is expected to be sufficiently high compared to potential production, we nevertheless expect future exploration to be imperfect and therefore have constrained the model with an "exploration cap." This serves as a limit on how efficient we might be as explorers and limited the model to extracting no more than 10% of the global in-place resource at any time. When this cap is reached, the modeled production declines, similar to expectations for oil production following "peak oil." Figure S3 illustrates the suite of model simulations' production curves; modeled production follows the specified production curve (Eq. 14) until the exploration cap of 10% is reached, at which point production declines to near zero. Figure S4 shows the percent of model runs that have reached the exploration cap through time. By 2100, the model predicts a probability of >94% that we will continue to meet the expected demand and will not be limited by this exploration cap. By 2200, that probability is ~75%.

The model considers the transient effect of anthropogenic production on reducing the in-place resource of geologic hydrogen. When this mass of trapped hydrogen is reduced, continued generation and trapping of hydrogen may replenish the reservoirs (M_F). We term this refilling rate as the "renewable" component of hydrogen. This annual renewable flux is illustrated in fig. S3 as the near-zero stable annual production after the exploration cap has been reached. The annual renewable flux is shown in Fig. 5 and has a P50 of 5 Mt year^{-1} with a log-normal distribution.

Calculation of energy equivalence

The Energy Information Administration estimates global proven reserves of natural gas to be 7257 trillion cubic feet as of 1 January 2020 (*100*), which equates to 205.5 trillion m^3. Using a density of 0.78 kg m^{-3} (*101*), this equates to 1.6×10^{14} kg of natural gas. The energy content of natural gas is variable, but assuming an average value of 52.2 MJ kg^{-1} from the Argonne National Laboratory GREET model (*102*), all the proven natural gas reserves of the world contain approximately 8.4×10^{15} J of energy. Using an energy density value for hydrogen of 141.9 MJ kg^{-1} (*102*), we can estimate that if 2% of the most probable amount of in-place geologic hydrogen (~5.6×10^6 Mt) could be recovered, that would amount to ~100,000 Mt of hydrogen, which contains about 1.4×10^{16} J of energy, or roughly twice as much energy as is stored in all the proven natural gas reserves on Earth.

Supplementary Materials

This PDF file includes:
MATLAB Scripts for Model Solution
Figs. S1 to S4
Table S1

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Appendix E. Recommendations on research and coordination

Request: Increased federal coordination and Investment in research to assess the potential of geologic hydrogen as a significant energy resource the United States including Alaska

Why? Federal science and resource agencies have not recognized geologic hydrogen's potential as an energy resource that could play a significant role in the energy transition. Geologic hydrogen in Alaska could provide a significant economically and environmentally preferred fuel in areas outside the North Slope and Cook Inlet.

Specific recommendations:

- To vastly accelerate research and analysis of geologic hydrogen, a dramatic increase in scientific research, research coordination, and analysis of geologic hydrogen is needed. Prioritizing and funding this effort is much more likely to occur if Congress passes legislation similar to the Methane Hydrate Research and Development Act.

- Increased funding and coordination are needed among the National Science Foundation (NSF), the Department of Energy (IDOE), the US Geological Survey I(USGS), the Bureau of Land Management, the Department of Defense (USAF) and the State of Alaska, similar to ongoing efforts on critical minerals or historical efforts on baseline topographic mapping.

- The University Alaska and other prominent US and international universities and geologic surveys appear to be willing to work together on an Arctic geologic hydrogen research partnership. Their involvement will bring needed capacity. NSF, USGS, State of Alaska and DOE coordination and joint funding could enable this.

- There is industry support for a research program, and a private-public partnership component should be considered.