U.S. DEPARTMENT OF ENERGY
Fossil Energy and Carbon Management

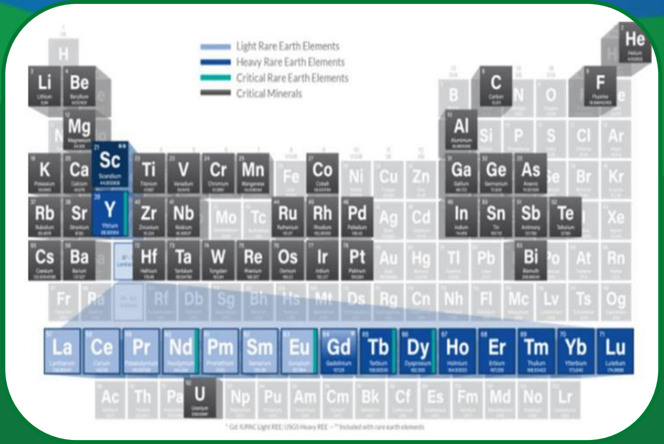
Natural Gas Decarbonization and Hydrogen Technologies (NG-DHT): Underground Hydrogen Storage

Infrastructure Strategies to Enable Deployment in High-Impact Sectors Workshop

January 17-18, 2024

Denver, CO





Methane Mitigation Technologies Division

Methane Emissions Mitigation

Advanced materials, data management tools, inspection and repair technologies, and dynamic compressor R&D for eliminating fugitive methane emissions across the natural gas value chain

Methane Emissions Quantification

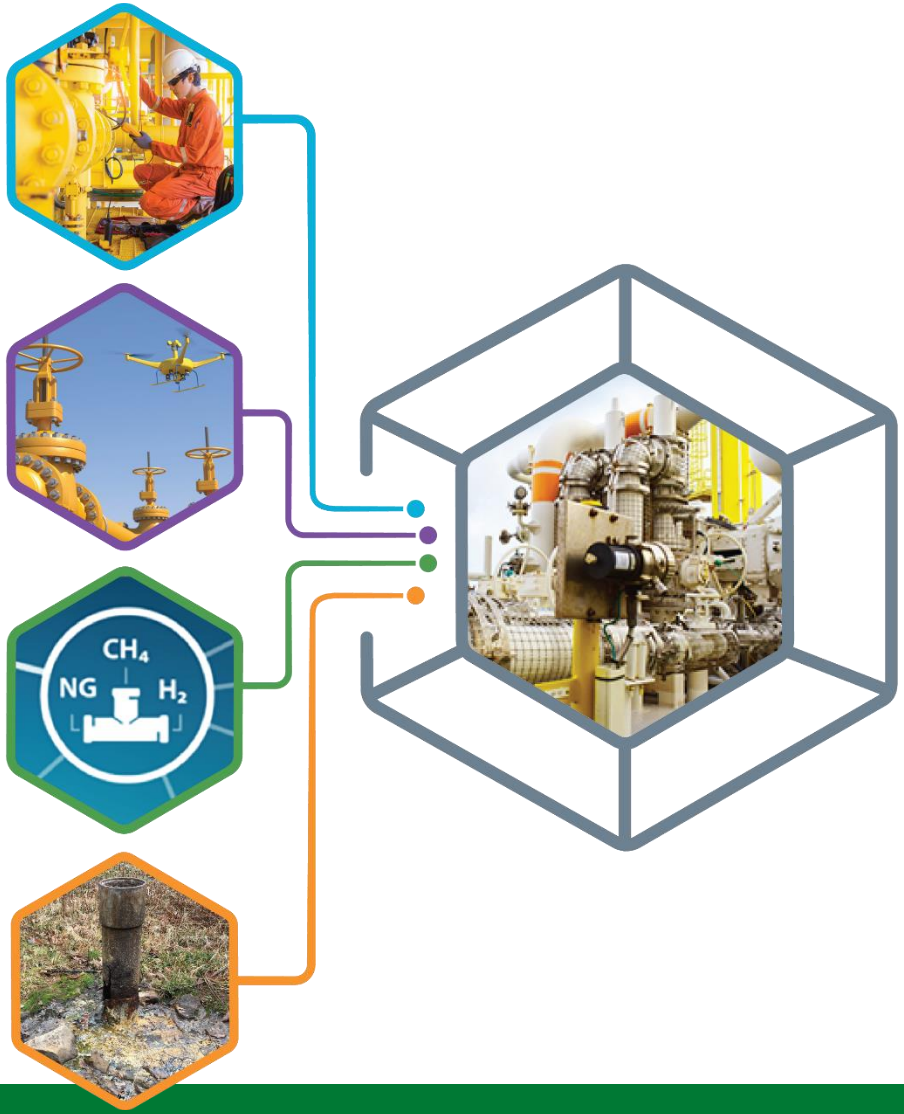
Direct and remote measurement sensor technologies and collection of data, research, and analytics that quantify methane emissions from point sources along the upstream and midstream portion of the natural gas value chain

Natural Gas Decarbonization and Hydrogen Technologies

Technologies for clean hydrogen production, safe and efficient distribution, and geologic storage technologies supported by analytical tools and models

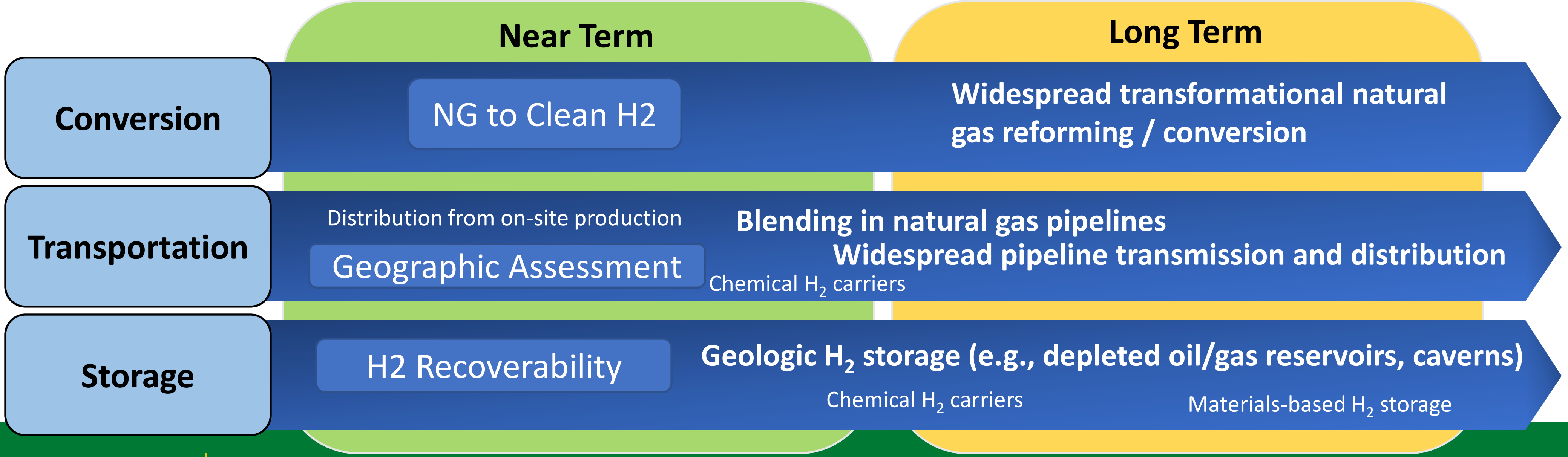
Undocumented Orphaned Wells Research

Developing tools, technologies, and processes to efficiently identify and characterize undocumented orphaned wells in order to prioritize them for plugging and abandonment.



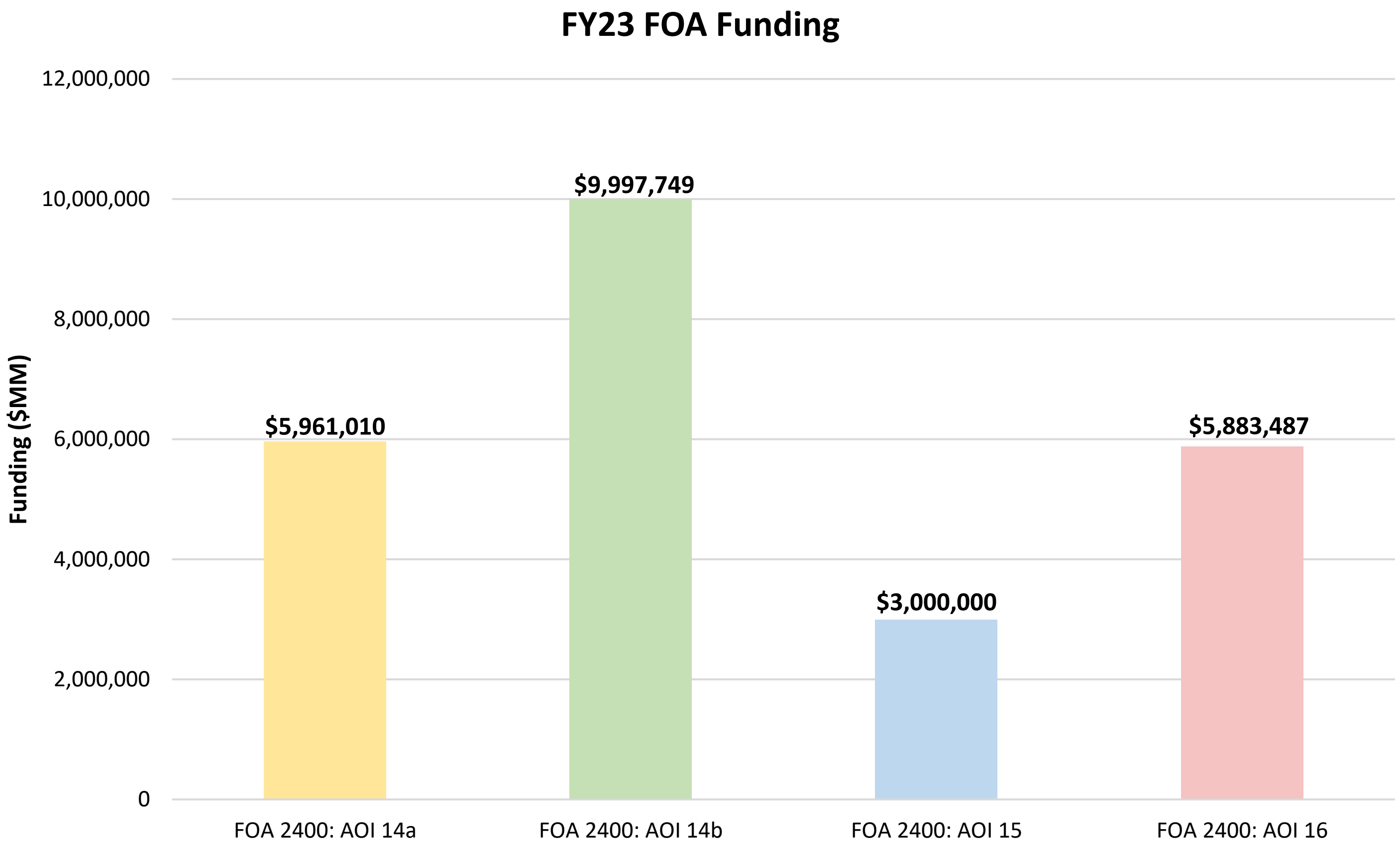
Natural Gas Decarbonization and Hydrogen Technologies

- The **Natural Gas Decarbonization and Hydrogen Technologies** (**NG-DHT**) Program was formally initiated in 2022 Omnibus.
- The NG-DHT Program coordinates with other DOE offices to support the transition towards a clean hydrogen-enabled economy through the decarbonization of natural gas conversion, transportation, and storage.
  - Supports transformational concepts for clean hydrogen production from domestic natural gas resources, with emphasis on decarbonization opportunities and value tradeoffs within energy markets.
  - Works to ensure the suitability of existing natural gas pipelines and infrastructure for hydrogen distribution, while emphasizing technology opportunities to detect and mitigate emissions.
  - Identifies underground storage infrastructure to handle high-volume fractions of hydrogen, while seeking demonstration opportunities for novel bulk storage mechanisms.



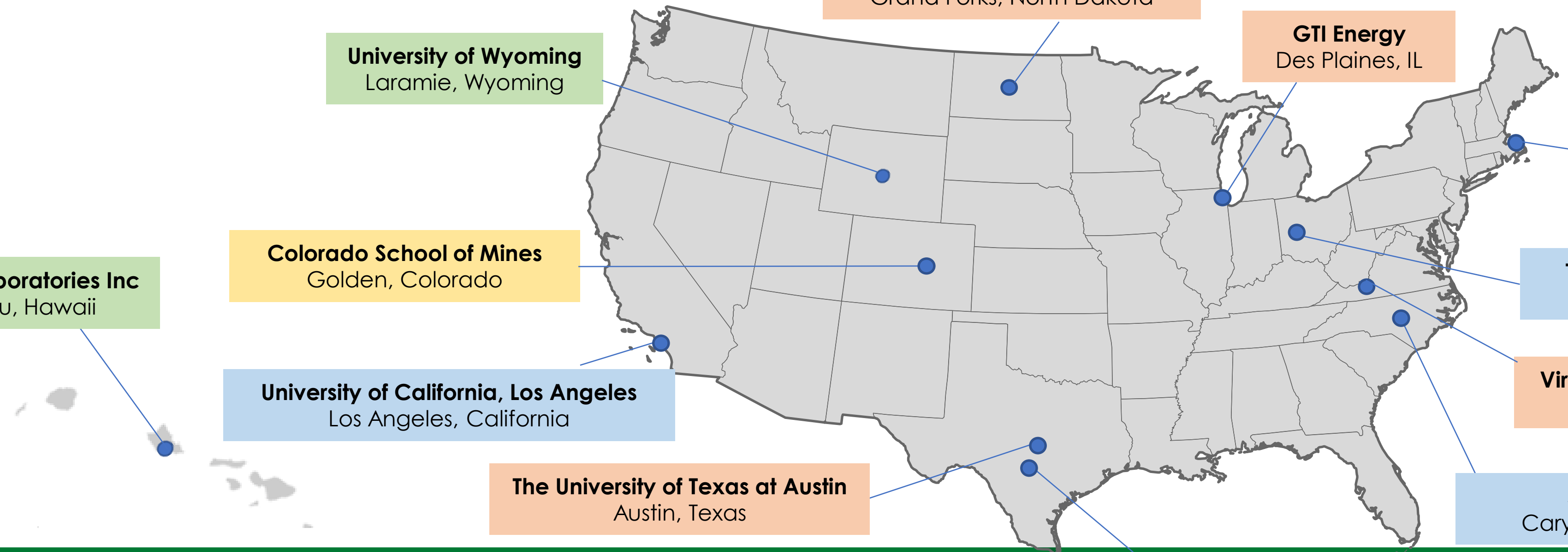
FOA2400 - Fossil Energy Based Production, Storage, Transport and Utilization of Hydrogen Approaching Net-Zero or Net-Negative Carbon Emissions

FOA 2400 Clean Hydrogen Production, Storage, Transport and Utilization to Enable a Net-Zero Carbon Economy	Area of Interest 14a: Methane Pyrolysis/Decomposition, In situ Conversion, or Cyclical Chemical Looping Reforming
	Area of Interest 14b: Hydrogen Production from Produced Water
	Area of Interest 15: Technologies for Enabling the Safe and Efficient Transportation of Hydrogen Within the U.S. Natural Gas Pipeline System
	Area of Interest 16: Fundamental Research to Enable High Volume, Long-term Subsurface Hydrogen Storage



FOA2400 - Fossil Energy Based Production, Storage, Transport and Utilization of Hydrogen Approaching Net-Zero or Net-Negative Carbon Emissions

AOI	Performer	Project Title	DOE Share	Non-DOE Share	Total Cost
14A	The Ohio State University	Bench Scale Testing and Development of Fixed Bed Chemical Looping Reactor for Hydrogen Generation from Natural Gas with CO2 Capture	$ 1,499,238	$ 375,000	$ 1,874,238
14A	Massachusetts Institute of Technology	Lower Cost, CO2 Free, H2 Production via CH4 Pyrolysis in Molten Tin	$ 1,500,000	$ 375,048	$ 1,875,048
14A	Susteon Inc.	Thermo-Catalytic Co-Production of Hydrogen and High-Value Carbon Products from Natural Gas using Structured Materials	$ 1,500,000	$ 375,000	$ 1,875,000
14A	University of California, Los Angeles	Direct Solar Self-Catalyzing Pyrolysis of Natural Gas to Hydrogen and High-Quality Graphite	$ 1,461,772	$ 377,848	$ 1,839,620
14B	University of Wyoming	Integration of Produced Water Thermal Desalination and Steam Methane Reforming for Efficient Hydrogen Production	$ 4,997,749	$ 4,999,387	$ 9,997,136
14B	Oceanit Laboratories Inc	HALO: Hydrogen-Recovery Using an AI-Arc-Plasma Learning Operational System for Produced Water	$ 5,000,000	$ 5,000,000	$ 10,000,000
15	Colorado School of Mines	Assessment of Toughness in H-Containing Blended Gas Environments in High Strength Pipeline Steels	$ 1,500,000	$ 375,000	$ 1,875,000
15	Southwest Research Institute	Technologies for Enabling The Safe and Efficient Transportation of Hydrogen within the U.S. Natural Gas Pipeline System	$ 1,500,000	$ 375,000	$ 1,875,000
16	GTI Energy	Developing & Investigating Subsurface Storage Potential And Technical Challenges for Hydrogen (DISSPATCH H2)	$ 1,400,000	$ 350,000	$ 1,750,000
16	University of North Dakota EERC	Williston Basin Resource Study for Commercial-Scale Subsurface Hydrogen Storage	$ 1,500,000	$ 375,000	$ 1,875,000
16	The University of Texas at Austin	Hydrogen Storage in Salt Caverns in the Permian Basin: Seal Integrity Evaluation and Field Test	$ 1,483,488	$ 370,873	$ 1,854,361
16	Virginia Polytechnic Institute	Assessment of Subsurface Hydrogen Storage in Depleted Gas Fields of Appalachia	$ 1,500,000	$ 375,000	$ 2,250,000
			$ 24,842,247	$ 13,723,156	$ 38,940,403



SHASTA Project Objective and Goals

Identify and **address key technological hurdles** and **develop tools and technologies** to enable broad public acceptance for **subsurface storage** of pure hydrogen and hydrogen/natural gas mixtures

Project Goals:

- ✓ Quantify operational risks
- ✓ Quantify potential for resource losses
- ✓ Develop enabling tools, technologies, and guidance documents
- ✓ Develop a collaborative field-scale test plan in partnership with relevant stakeholders

SHASTA
Subsurface Hydrogen Assessment, Storage, and Technology Acceleration

NATIONAL ENERGY TECHNOLOGY LABORATORY

Pacific Northwest NATIONAL LABORATORY

Sandia National Laboratories

Lawrence Livermore National Laboratory

Project Organization

Research Focus

Research Thrusts
- Risk Quantification (Experiment & Simulation)
- Enabling Technologies to Manage Hydrogen Storage
- Recommended Practices and Industry Engagement

S&T Outcomes
- Core- to reservoir-scale performance
- Materials compatibility
- Role of microbial interactions
- Simulation and monitoring tools
- Scientifically informed pilot test plan(s)

Structure

Project Direction
- DOE-FECM IAA with DOT-PHMSA
- NETL-Program

Project Advice
- Stakeholder Group

April 2- 4, 2024
Resource Sustainability Project Review Meeting at the Wyndham Grand Hotel in Pittsburgh, PA

Project Execution
- PNNL
- NETL-RIC
- LLNL
- SNL
- Industry Partner(s)

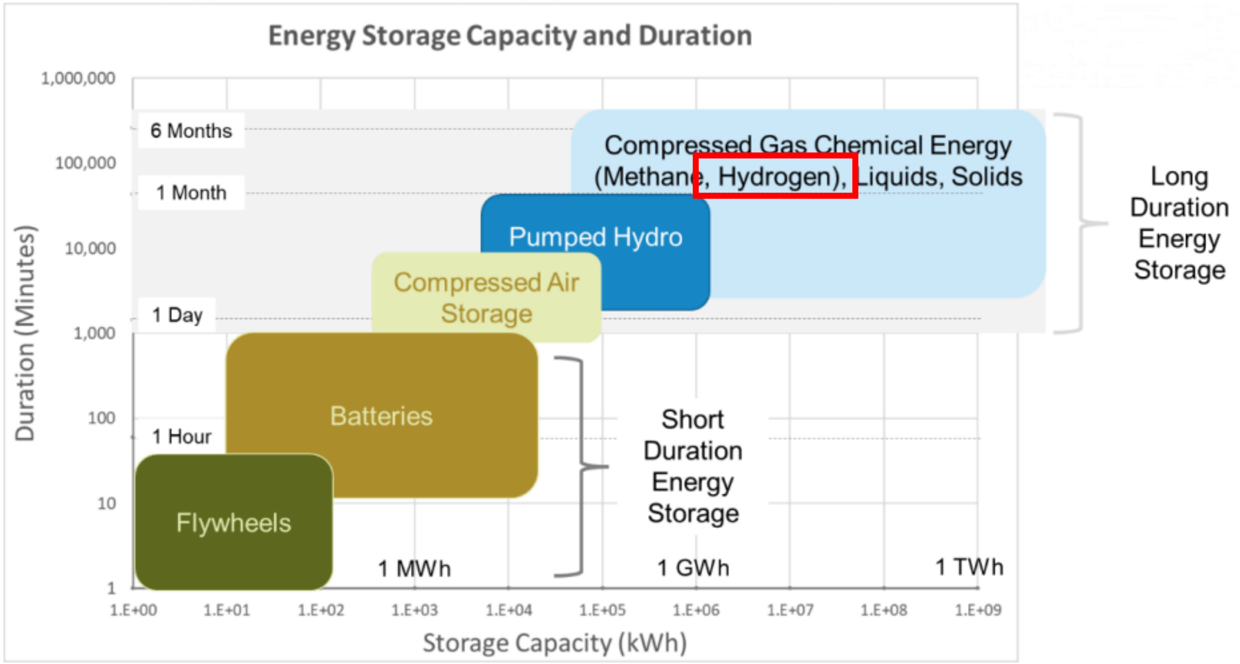
Hydrogen as an Enabler to a Low-Carbon Future

Significant potential

- A flexible fuel with many end uses
- Potential for very large-scale energy storage

Need

- Provide long-term, safe, effective regional subsurface storage to ensure reliability of hydrogen energy supply



Advantages of Underground Gas Storage (vs. Tank)

✓Storage capacity

- Reservoirs and caverns can accommodate long-duration (seasonal) storage
- Gas can be stored at greater pressure and mass density than in storage tanks

✓Storage cost

- Geologic structure is the containment vessel
- Construction costs are primarily those associated with the injection/withdrawal well infrastructure, which are less than the cost of storage tanks

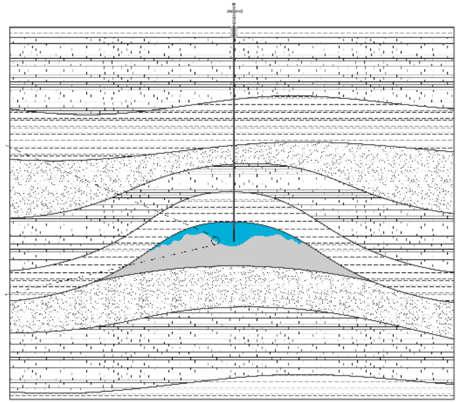
✓Surface footprint

- Land area occupied by well pads and pipelines is smaller than that of storage tanks

✓Storage safety

- Storage formation is physically separated from risk factors, such as oxygen, ignition sources and floods, which reduces the vulnerability to fire, extreme climate events, and sabotage

~300 – 10,000 kg H_2

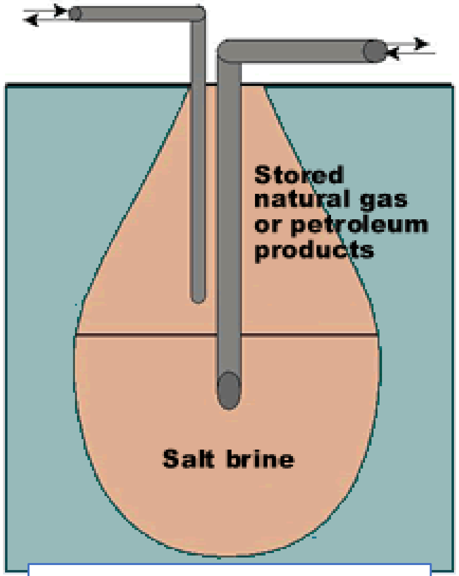


~3,000,000 – 30,000,000 kg H_2

Storage Reservoir Types

4 main types of underground gas storage

Salt Cavern

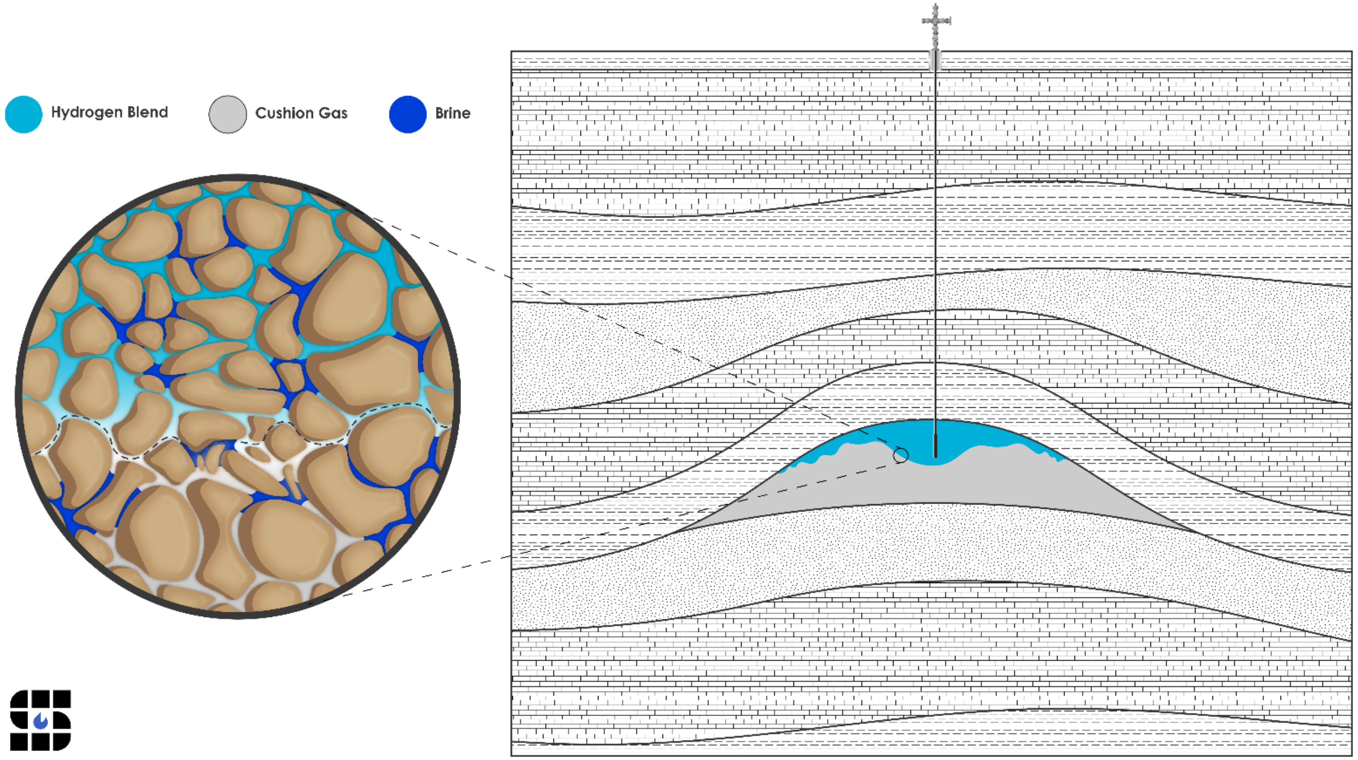


https://www.phmsa.dot.gov/pipeline/underground-natural-gas-storage/fact-sheet-underground-natural-gas-storage-caverns

Hard Rock Cavern

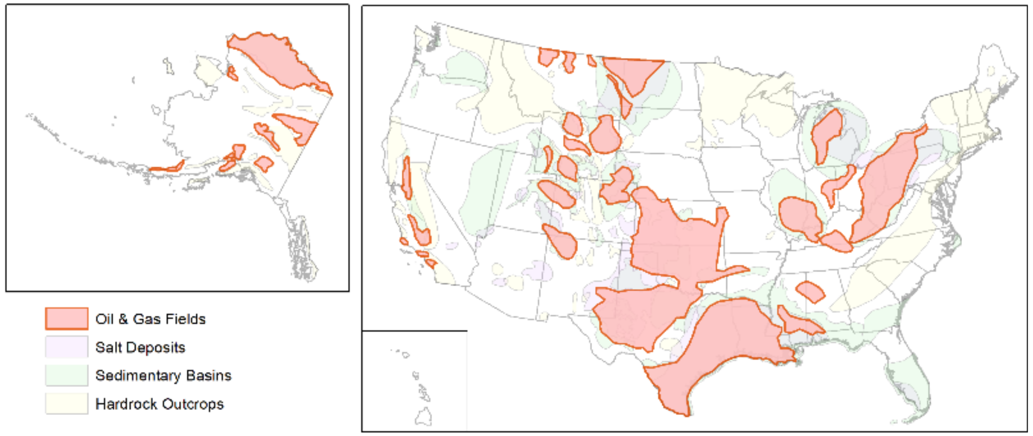
https://www.encyclopedie-environnement.org/en/soil/underground-storage-gas-and-hydrocarbons-prospects-for-energy-transition/

Depleted Reservoirs & Brine Aquifers

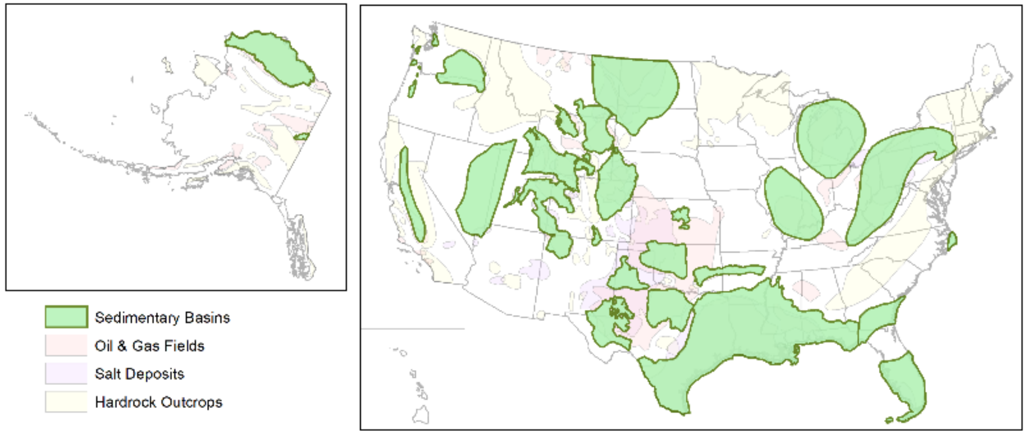


Storage Reservoir Types Across the U.S.

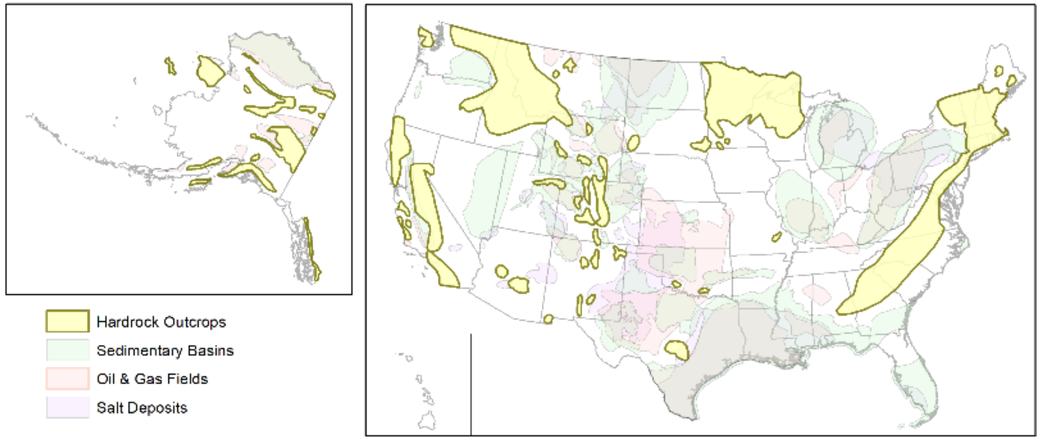
Oil and Gas Fields in the United States



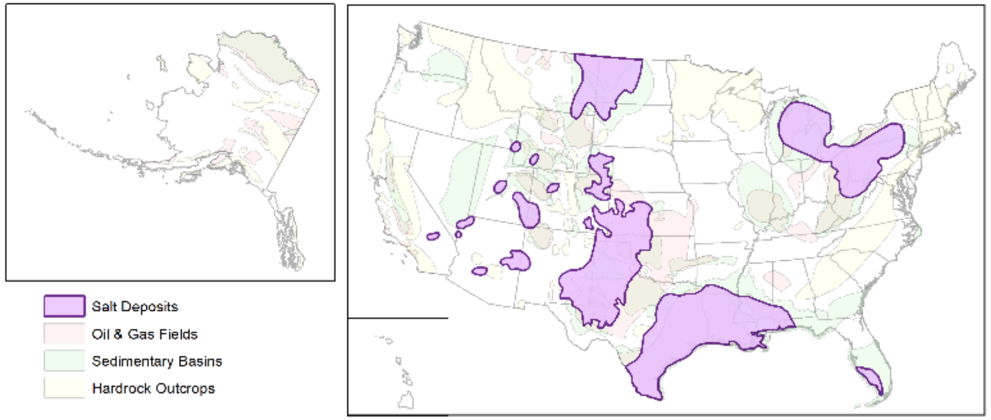
Sedimentary Basins in the United States



Hardrock Outcrops in the United States

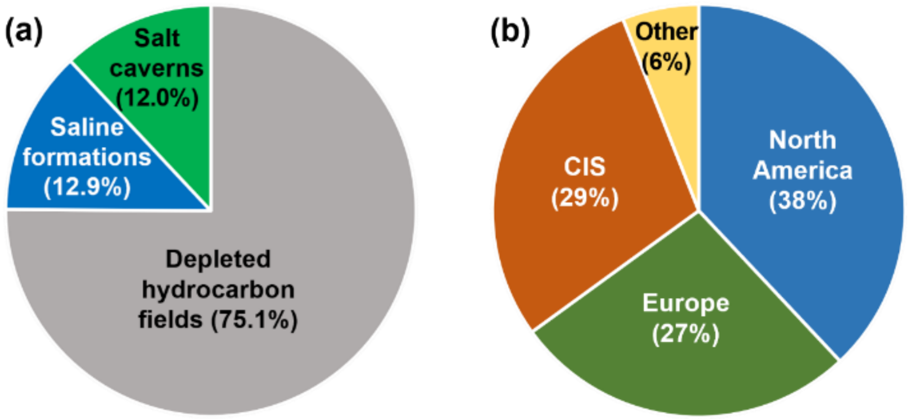


Salt Deposits in the United States



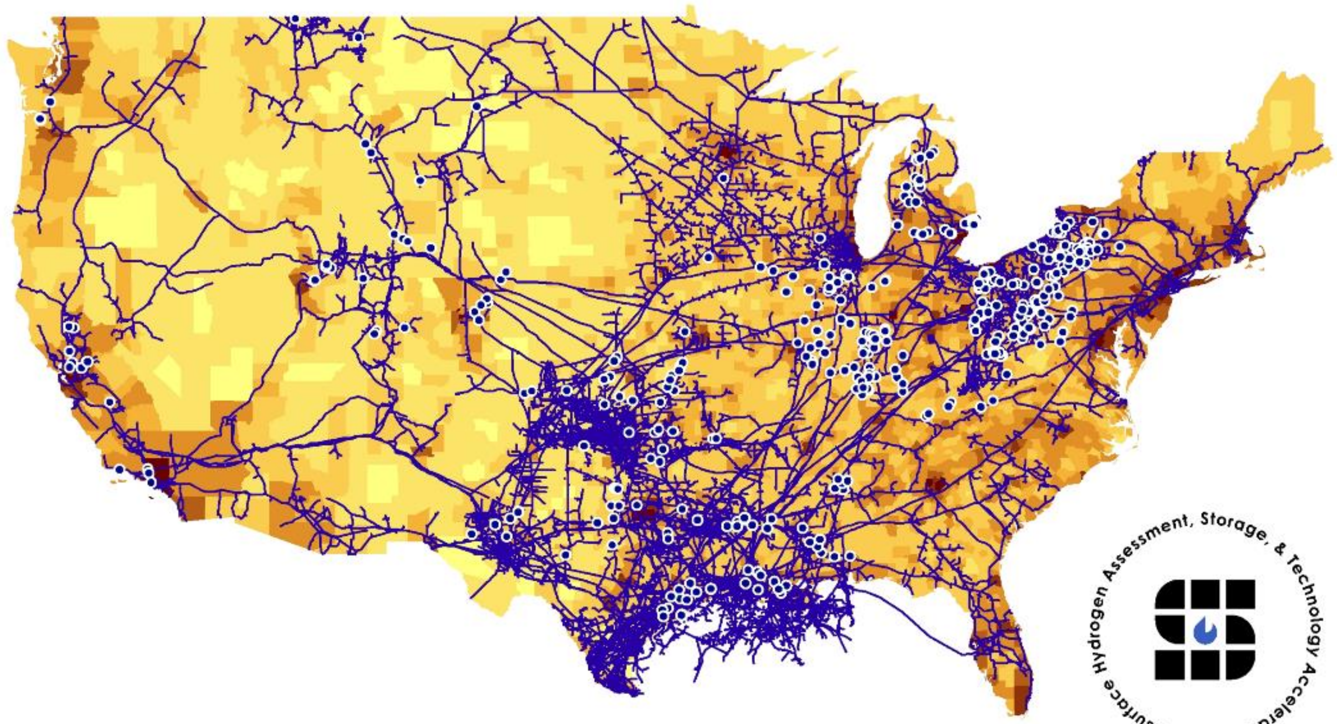
Underground Natural Gas (UGS) Storage Infrastructure

- UGS has provided long-duration storage for more than 100 years, primarily to meet seasonally-variable heating demand.
  - What is the impact of H_2 blending on underground energy storage?
  - Can existing UGS facilities be converted to underground hydrogen storage (UHS) to sufficiently buffer prospective H_2 demand?



Breakdown of UGS storage volumes by storage types (a) and by region (b)

- UGS sites are distributed throughout the United States and are often located near large population centers, where NG gas demand is greatest.

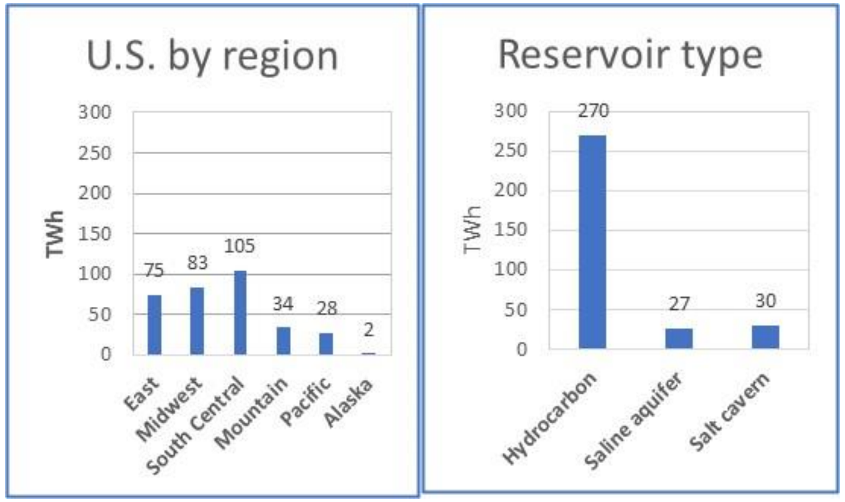


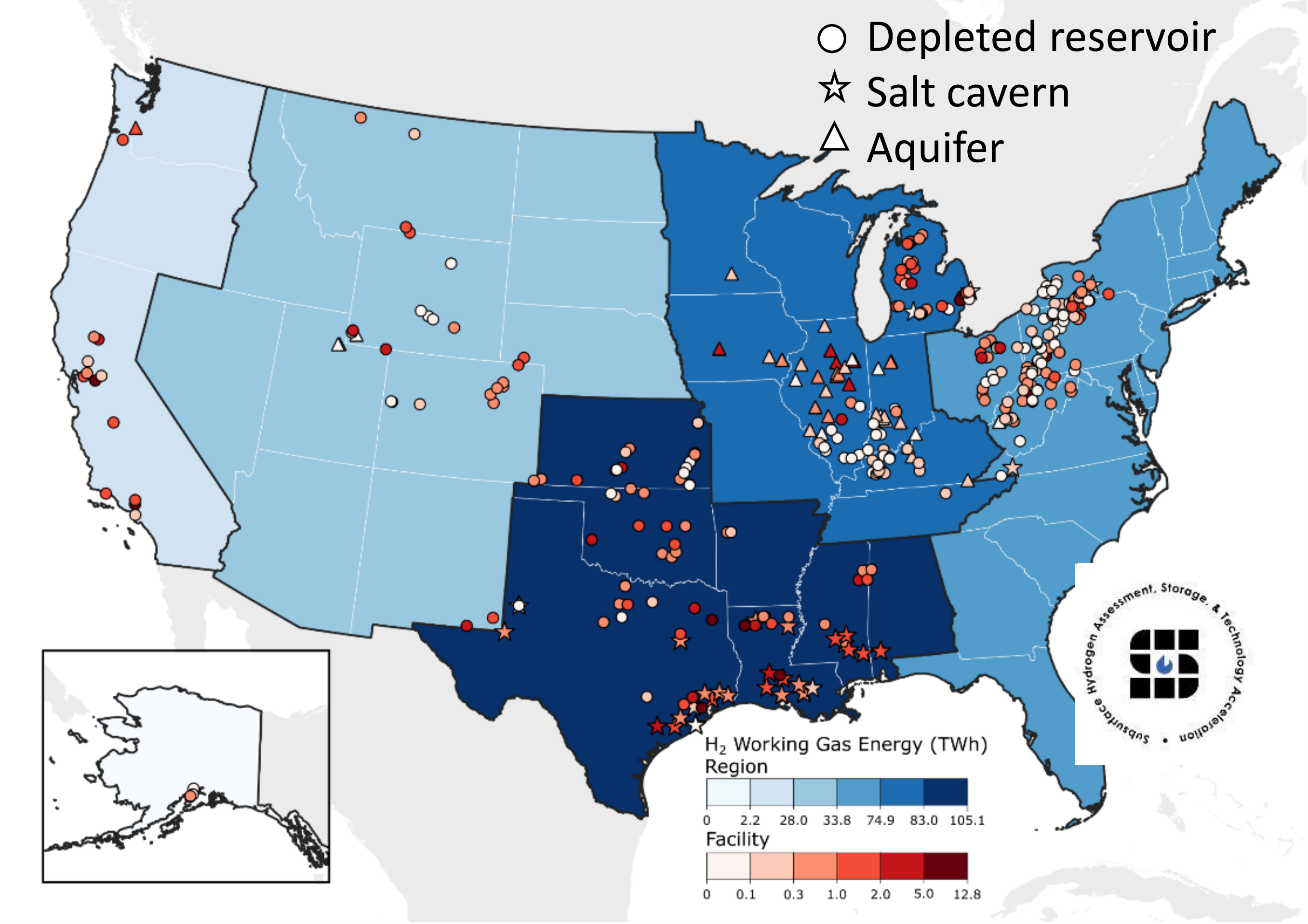
Subsurface Hydrogen Assessment, Storage, & Technology Acceleration

H2 Energy Storage Potential in Existing UGS Facilities

Conversion of working gas energy (WGE) for natural gas to hydrogen results in a 75% reduction of 1,282 TWh (92.3 MMT) to 327 TWh (9.8 MMT)

Assuming 100% H_2





- ✓ Lots of interest in blended storage (H_2 + natural gas)
- ✓ Many facilities operating below their max volume
- ✓ May need new sites depending on demand scenario

Lackey et al., 2023 (https://doi.org/10.1029/2022GL101420)

SHASTA-HELP Tool

SHASTA-HELP | MAP | CALCULATION | MANUAL | CONTACT US | SHASTA WEBSITE

Hydrogen Estimator for Logistical Planning Tool, V. 1.0.0

Intended Use

This tool contains functionality for estimating the storage potential of pure and blended natural gas-hydrogen mixtures in various subsurface formations and is intended to be used for pre-characterization or site screening purposes. Detailed storage analysis should be conducted by full reservoir simulation models.

AN EXISTING NATURAL GAS STORAGE FACILITY

A PROSPECTIVE GEOLOGIC FORMATION

Geophysical Research Letters

Research Letter | Open Access

Characterizing Hydrogen Storage Potential in U.S. Underground Gas Storage Facilities

Greg Lackey, Gerad M. Freeman, Thomas A. Buscheck, Foad Haeri, Joshua A. White, Nicolas Huerta, Angela Goodman

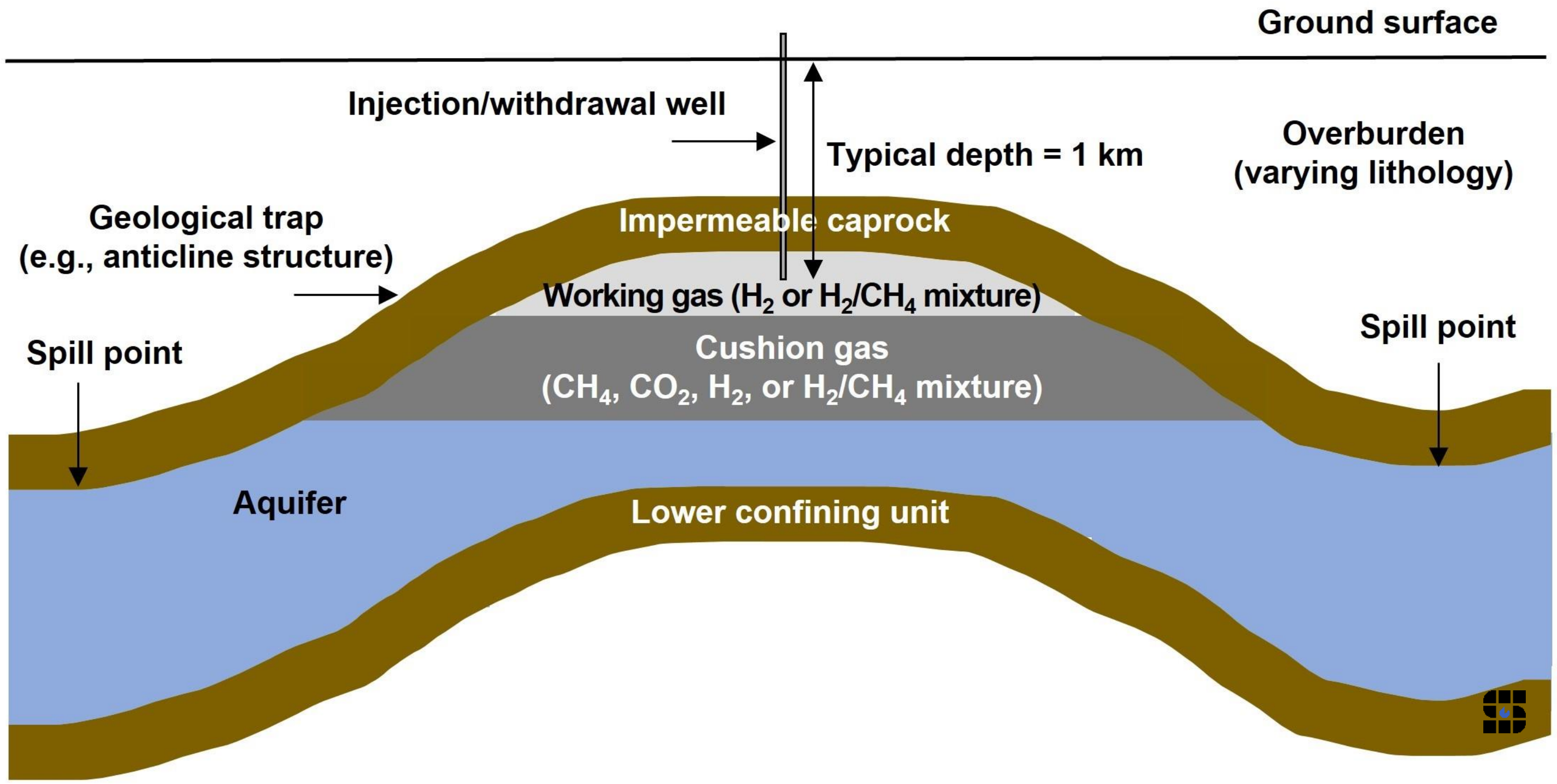
First published: 10 February 2023 | https://doi.org/10.1029/2022GL101420

https://shasta-help.pnnl.gov/

SHASTA-HELP

Considerations for Subsurface H2 Storage

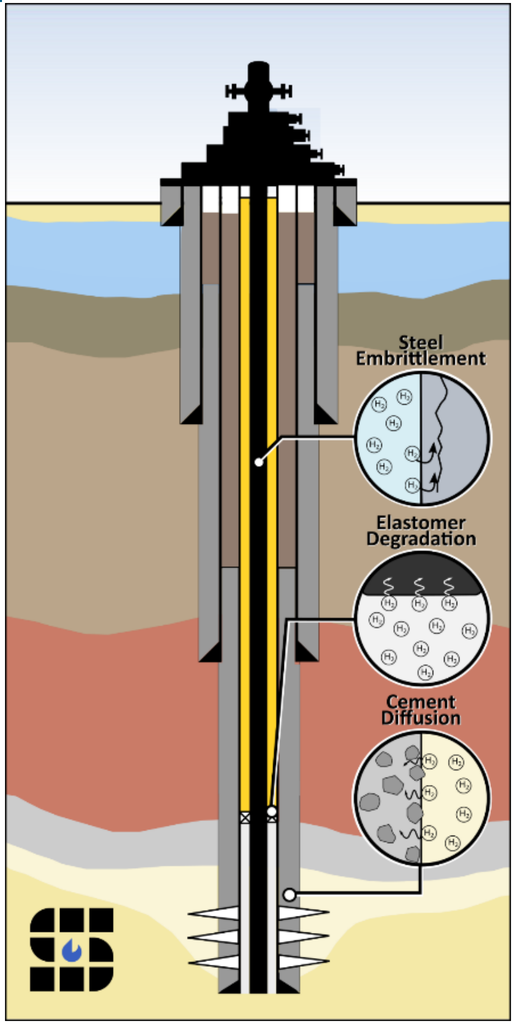
Underground Hydrogen Storage (UHS)



Key considerations

- ✓ Well integrity
- ✓ Microbiology & geochemistry
- ✓ Managing reservoir flow dynamics
- ✓ Techno-economics

Well Integrity



Well integrity is an important source of risk and liability for UHS

- Well integrity loss has been the source of most leakage events at natural gas storage sites
- H_2 is highly mobile in the subsurface and will potentially leak through faulty wells
- Well integrity must be maintained in injection, monitoring, and legacy wells

Steel embrittlement

- H_2 moves into the atomic structure of steel causing premature cracking and failure
- Commonly used low-carbon steels are susceptible
- Occurs when H_2 concentrations are high

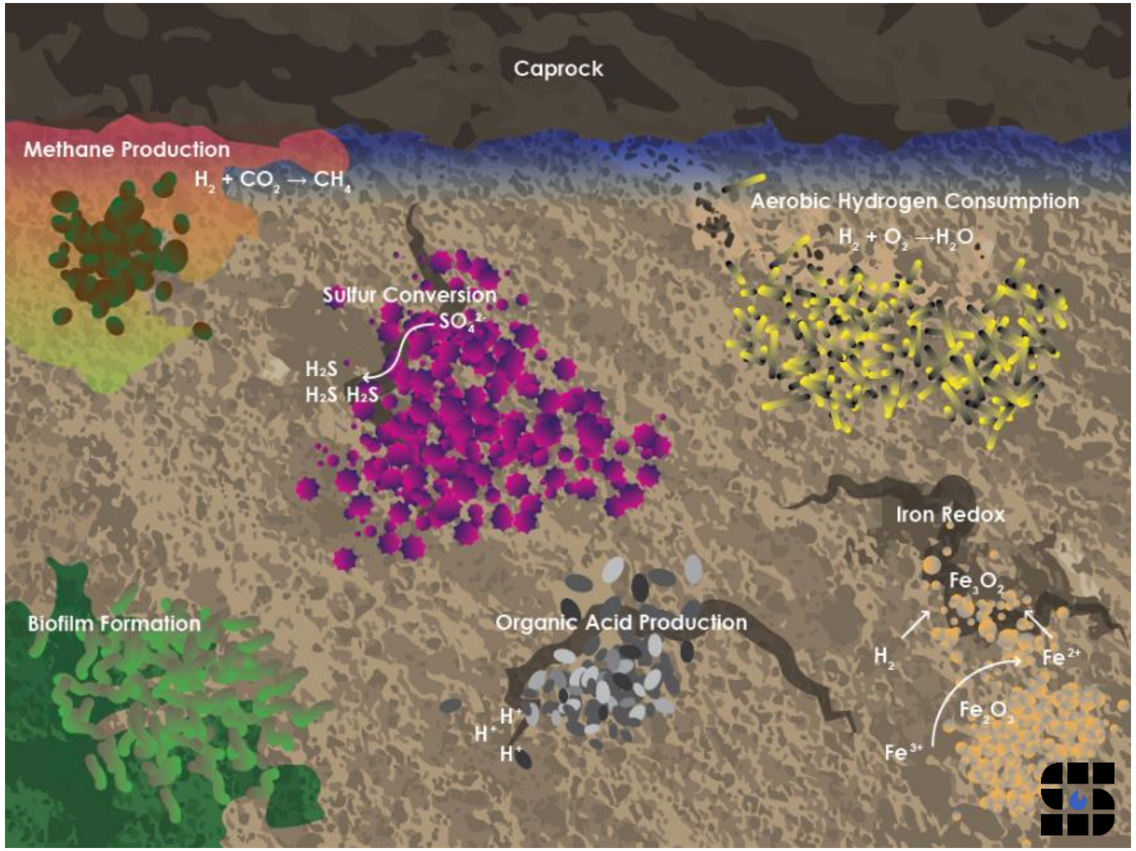
Elastomer degradation

- Damage can result from permeation of H_2 into the material followed by rapid decompression
- Other failure mechanisms may include temperature and chemical degradation, extrusion and nibbling, compression set, wear, and spiral failure

Cement diffusion

- H_2 is the smallest molecule and has a high diffusivity
- H_2 diffusivity in cement is expected to be more of a challenge than reactivity

Microbiology and Geochemistry Fundamentals

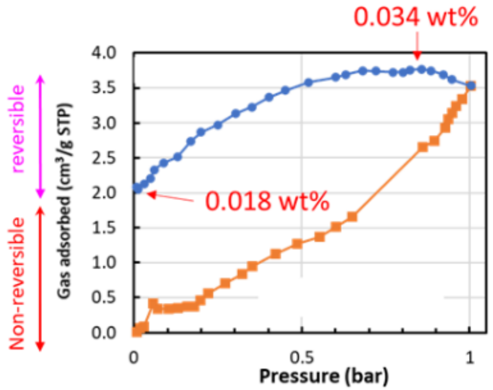


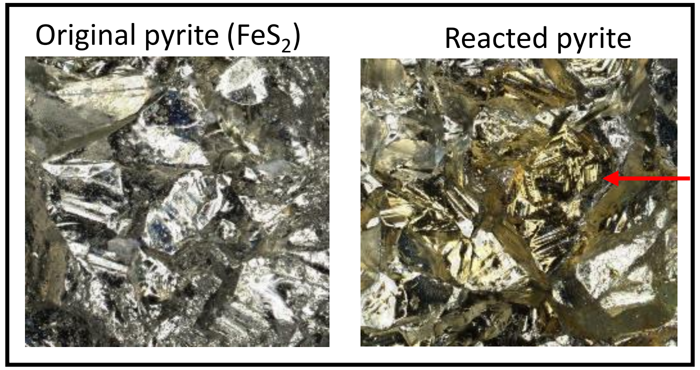
Microbial activity can affect subsurface energy storage through:

- Methanogenesis
- Hydrogen Sulfide Production
- Acid Production
- Microbiological Corrosion Pathways

Geochemical reactions between H_2, formation fluids, and rock mineralogy may lead to:

- Loss of H_2
- Contamination of stored H_2 by wanted gas generation (e.g., H_2S)
- Mineral dissolution/precipitation





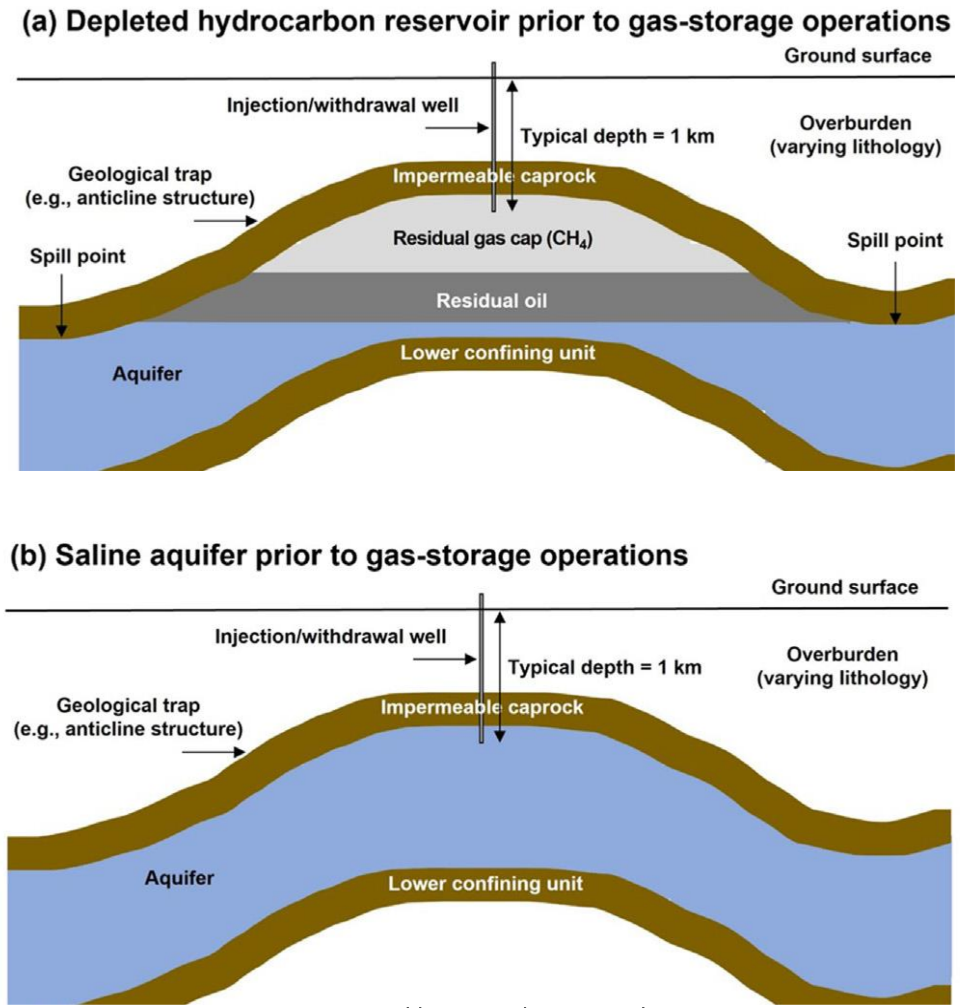
Reservoir Performance

Goal

- Investigate reservoir behavior when converting existing natural gas storage fields to UHS or creating new storage from depleted field or aquifer

Key questions

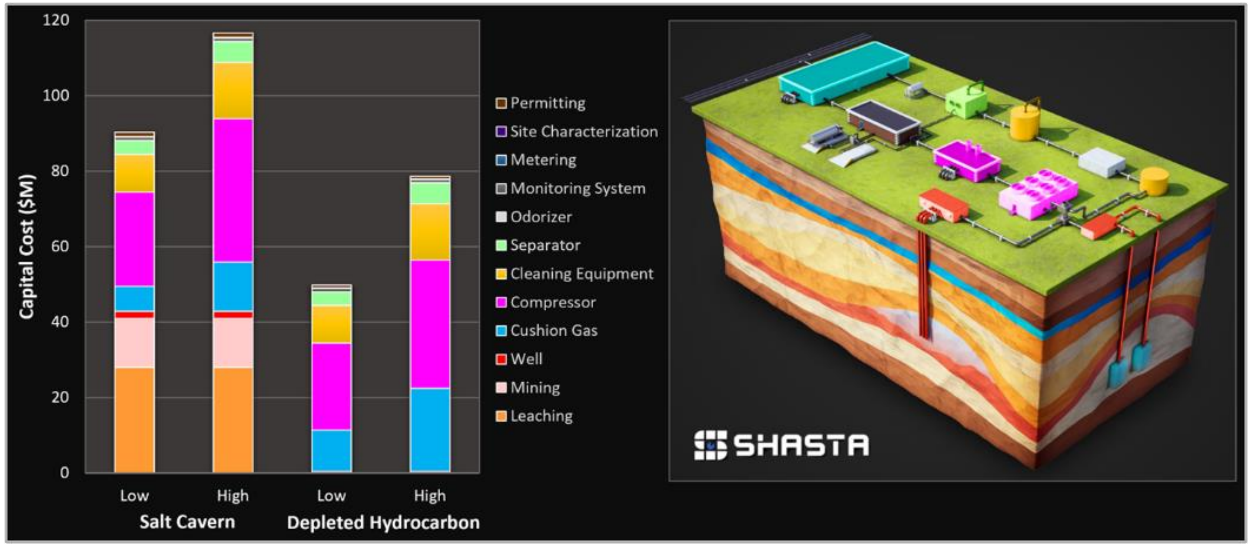
- What is the impact of rock and fluid properties on storage efficiency and energy availability?
- How can H_2 / NG / brine flow dynamics be managed?
- What mechanisms could lead to resource loss?
- To what extent can existing industrial workflows be re-used for H_2 projects?

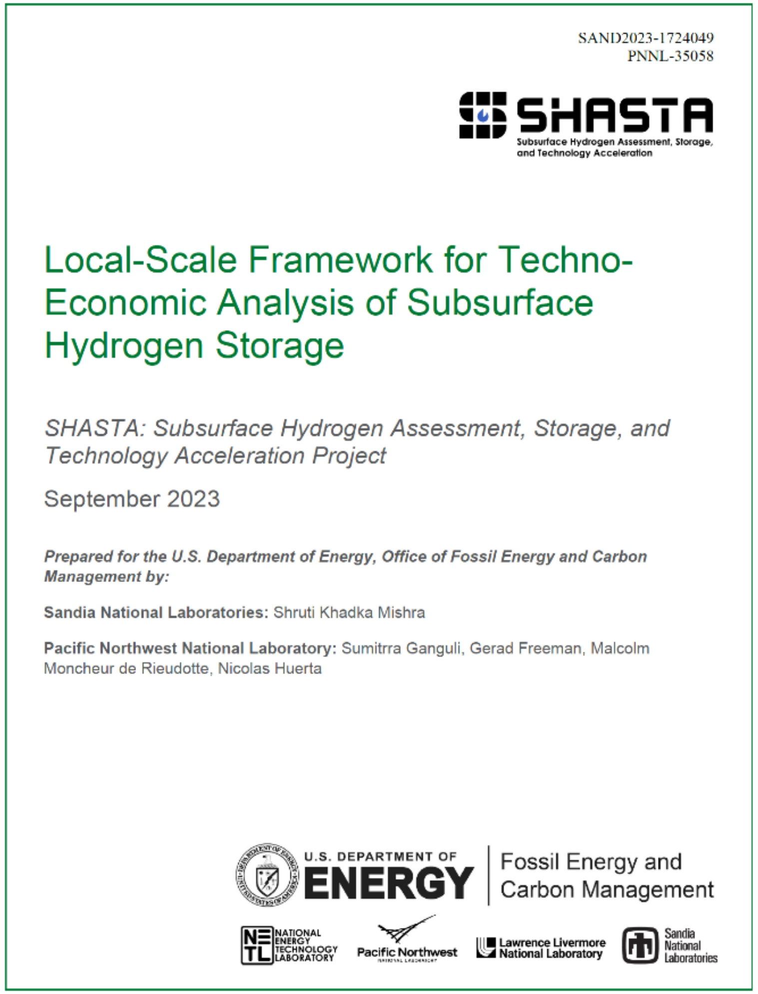


Buscheck et al. (2023) https://doi.org/10.1016/j.ijhydene.2023.07.073

Technoeconomic Analysis for UHS

- Framework for UHS cost estimation that reflects the granularity that an operator might use to assess their existing infrastructure or to identify opportunities to develop new facilities
  - ***https://www.osti.gov/servlets/purl/2202473***
- Present a hypothetical use case for Pennsylvania
- Working on a regional scale assessment methodology





SAND2023-1724049
PNNL-35058

SHASTA
Subsurface Hydrogen Assessment, Storage, and Technology Acceleration

Local-Scale Framework for Techno-Economic Analysis of Subsurface Hydrogen Storage

SHASTA: Subsurface Hydrogen Assessment, Storage, and Technology Acceleration Project

September 2023

Prepared for the U.S. Department of Energy, Office of Fossil Energy and Carbon Management by:

Sandia National Laboratories: Shruti Khadka Mishra

Pacific Northwest National Laboratory: Sumitrra Ganguli, Gerad Freeman, Malcolm Moncheur de Rieudotte, Nicolas Huerta

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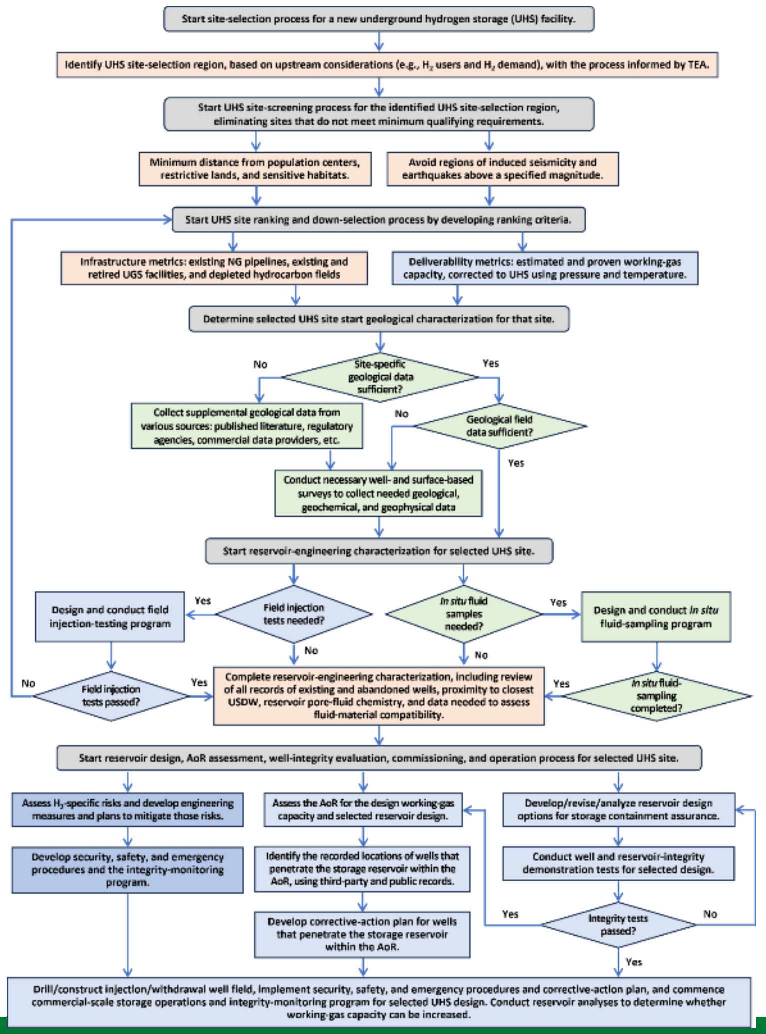
NATIONAL ENERGY TECHNOLOGY LABORATORY · Pacific Northwest · Lawrence Livermore National Laboratory · Sandia National Laboratories

Forward Look & Field Test



- Working on a recommended UHS project design and management workflow

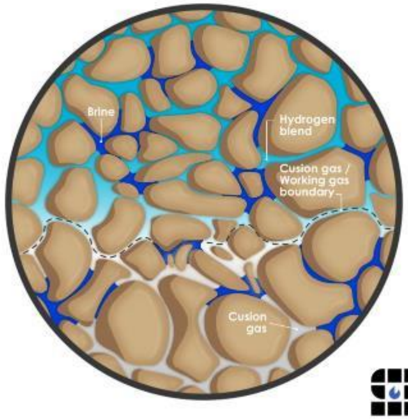
- Consistent with API 1170 and 1171 RPs

- *Key elements*
  1. Site selection
  2. Site characterization
  3. Engineering design
  4. Field testing and commissioning
  5. Operations
  6. Emergency response

- Will be used to structure final report deliverables
  - Geologic characterization & ranking of candidate sites
  - Risk assessment for UHS
  - Facility and regional-scale Technoeconomic framework

Forward Look & Field Test

- **Additional deliverables coming out of SHASTA**
  - Code comparison study for reservoir simulations
  - Geologic screening study for several locations (PA, AK)
  - Multiphase flow study in rocks
  - Material performance in H_2 environments (cement/steel)
  - Materials performance for reservoir and caprock under abiotic and biotic conditions
  - Continuous updates to SHASTA help tool (e.g., storage & delivery capability, GIS functionality)
  - Community engagement plan



Forward Look & Field Test

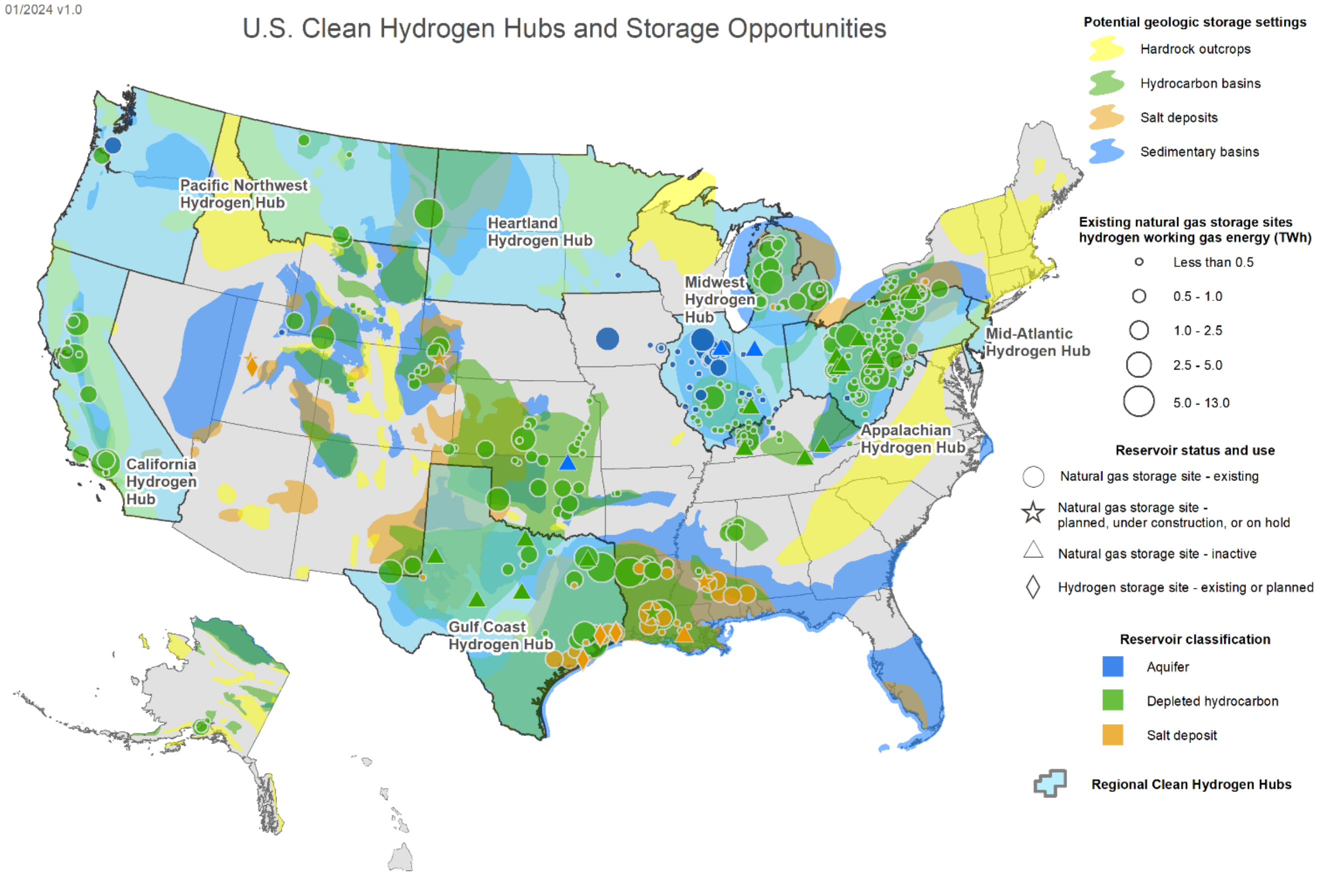
- SHASTA's ultimate goal is to enable field tests
- Continue to build relationships with industry
  - Quantify asset and resource risks
  - Reduce uncertainty in operations
  - Characterize site-specific behavior
- Looking for site owners who may be interested in pilot-scale studies
  - Site characterization & risk assessment
  - Small pilot-scale demonstration at single well
  - Larger field-scale operations
- End of SHASTA deliverable is a plan for field test

Forward Look & Field Test

New Project: Lawrence Berkely National Laboratory - *New Geophysical Tools for Monitoring Geologic Hydrogen Storage*

Subsurface Hydrogen Assessment, Storage, and Technology Acceleration – 2024 Workshop, April 3, 2024, Pittsburgh, PA

- Present a dive into final SHASTA deliverables
- Invite complimentary efforts to present
  - International efforts
  - Complimentary R&D
    - HFTO projects
    - USGS
    - FOA-2400 projects
    - H_2 Hubs
  - Industry & regulatory perspective
- Discuss next step needs in UHS for research, industry, and regulators



Hydrogen working gas energy of active natural gas storage sites from Lackey et al., 2023
Locations of existing natural gas storage sites (source: PHMSA)
Locations of inactive natural gas storage sites (source: EIA, HIFLD)
Generalized locations and capacities of existing Hydrogen storage locations are extracted from web resources
Generalized locations of natural gas storage sites in development represent that of the hosting county (source: EIA, FERC)
Clean Hydrogen Hubs represent the participating states in each Clean Hydrogen Hub announced by OCED.
Potential geologic storage settings from Lord et al., 2014 with additional contributions from Barry Roberts and Nora Wynn (SAND2023-04266R)

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Questions?