Underground Hydrogen Storage (UHS) in Depleted Reservoirs

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Acknowledgements

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Battelle Technical Team: Priya Ravi Ganesh, Aubrey Collie and Derrick James

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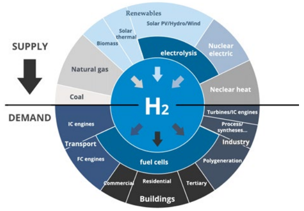
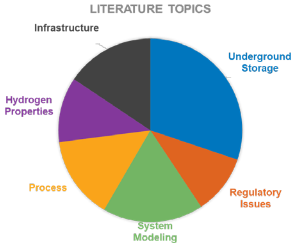
Outline

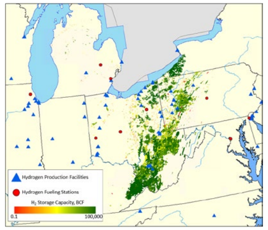
- Introduction



- Hydrogen in the Subsurface



- UHS Performance Assessment

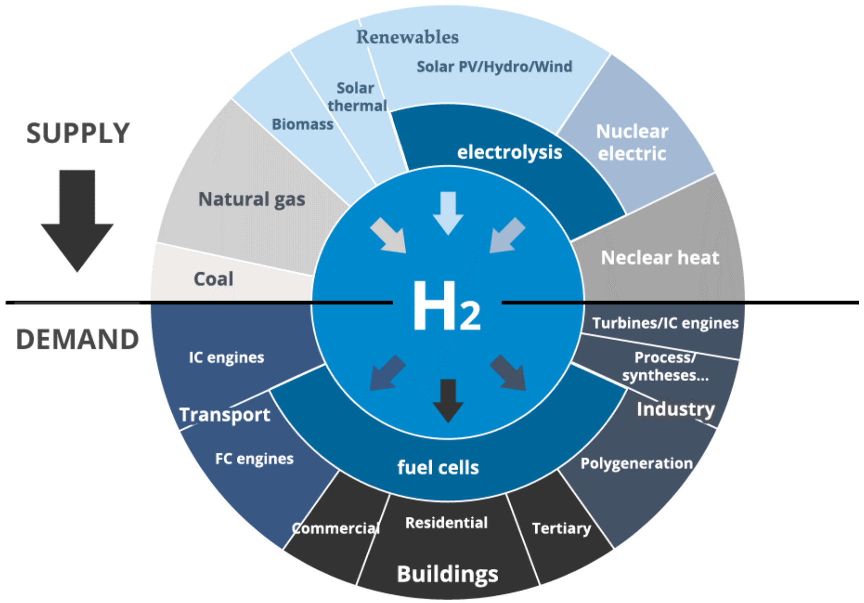


- Roadmap for Commercial UHS

Introduction

Hydrogen: Current and Planned Role

Both the number of applications and the market size of each application is likely to grow.



	Transportation Applications	Chemicals and Industrial Applications	Stationary and Power Generation Applications	Integrated/Hybrid Energy Systems
Existing Growing Demands	• Material-Handling Equipment • Buses • Light-Duty Vehicles	• Oil Refining • Ammonia • Methanol	• Distrubuted Generation: Primary and Backup Power	• Renewable Grid Integration (with storage and other ancillary services)
Emerging Future Demands	• Medium-and Heavy-Duty Vehicles • Rail • Maritime • Aviation • Contruction Equipment	• Steel and Cement Manufacturing • Industrial Heat • Bio/Synthetic Fuels	• Reversible Fuel Cells • Hydrogen Combustion • Long-Duration Energy Storage	• Nuclear/Hydrogen Hybrids • Gas/Coal/Hydrogen Hybrids with CCUS • Hydrogen Blending

Figure 1. Existing and emerging demands for hydrogen

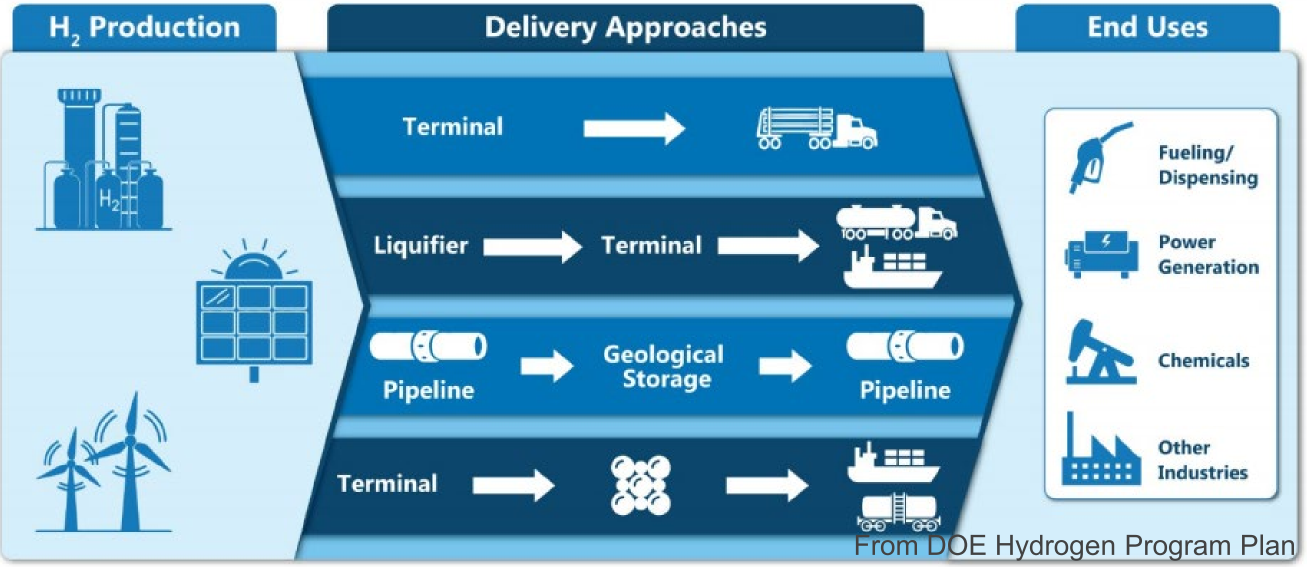
Source: U.S. Department of Energy Hydrogen Program Plan, 2020

Challenges as we scale up:

- Higher production costs,
- Intermittent renewable energy sources, and
- Need for more efficient storage and transportation solutions

Introduction

Large-Scale Hydrogen Storage Key for Balanced Hydrogen Value Chain



From DOE Hydrogen Program Plan

Study Goals:

- Literature review and preliminary performance assessment of underground hydrogen storage (UHS) in depleted reservoirs.
- High-level recommendations to advance the state-of-the-art understanding of design and integrity aspects of subsurface storage and related infrastructure for clean hydrogen economy.

Introduction
Large-Scale Hydrogen Storage Options

- Subsurface offers significant advantages over above-ground storage facilities for large-scale storage such as:
  - Lesser footprint: subsurface storage leverages higher volumetric energy density of hydrogen resulting in lesser area requirement required for large storage volumes.
  - Secure storage: subsurface storage is less susceptible to sabotage and environmental risk factors.
  - More availability: suitable subsurface storage reservoirs offer orders of magnitude higher storage capacity and are widely available.
- Among the geologic storage options, depleted reservoirs present a highly attractive storage option as they:
  - are well characterized with demonstrated performance from historical operations,
  - have proven structural trap,
  - offer substantial storage capacity, and
  - are cost-effective with existing infrastructure that can be leveraged for hydrogen storage.

Introduction
Scope

- Report presents insights into considerations for depleted reservoirs to be utilized for UHS and the fate of hydrogen in these systems in comparison with natural gas and CO_2 storage analogs.
  - Literature review of geologic UHS options.
  - Analogous industrial gas storage and UHS experience to date via industrial and research projects around the world.
- Understanding of hydrogen dynamics in the subsurface is achieved by the successful implementation of a preliminary performance assessment framework for analyzing feasibility of UHS options.
  - Demonstrate preliminary hydrogen storage performance assessment in subsurface conditions representative of depleted gas fields in the U.S. Midwest region.
  - Comparison of fundamental hydrogen dynamics in the subsurface against traditional or more familiar CO_2 and natural gas storage processes.
- High-level recommendations on primary technical, economic, and social considerations to facilitate successful and sustainable commercial deployment of potential UHS projects for policy makers, gas field owners/ operators and energy providers interested in exploring the hydrogen-power nexus.

Hydrogen in the Subsurface

Hydrogen in the Subsurface

- Analogous to underground natural gas storage operations that have been successfully implemented for over a century in salt caverns, depleted reservoirs, and aquifers.

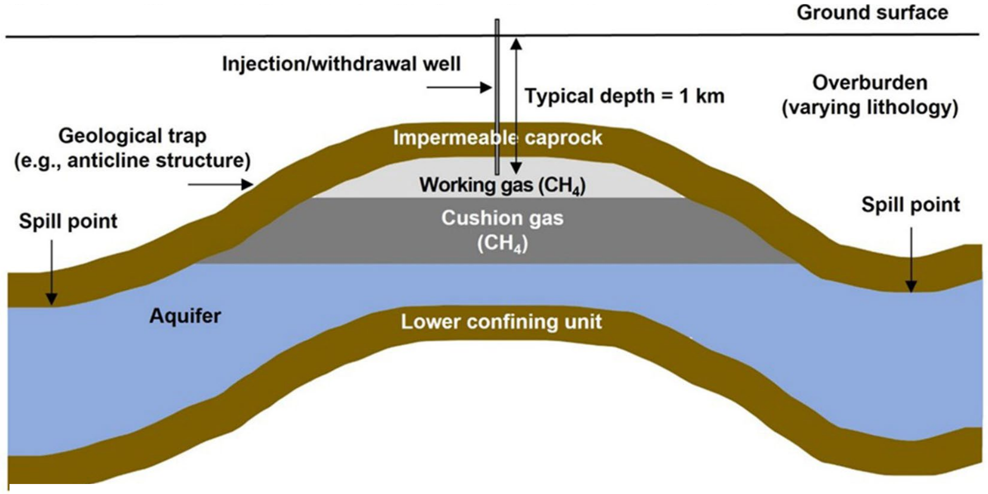
- Function: Provide storage capacity to balance seasonal supply and demand fluctuations and meet peak demand to stabilize the power grid.

- Infrastructure includes compressors and pipelines to transport hydrogen and wells to inject and produce hydrogen on demand.

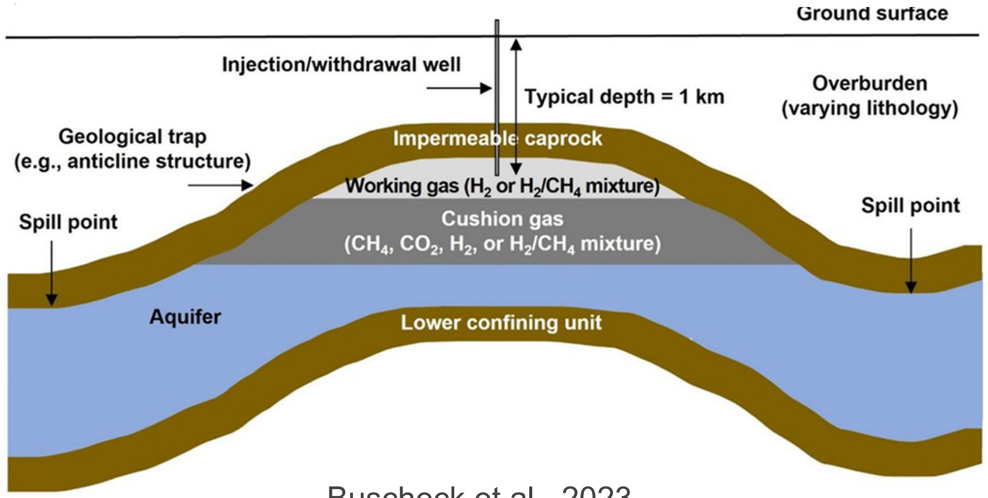
Requirements of geologic system for UHS suitability:

- High porosity, permeability in reservoir zone with surrounding rock sealing/ impermeable
- Structural and stratigraphic traps ideal to successfully contain gas
- Cushion gas requirements for gas withdrawal, sufficient pressure maintenance and storage integrity

Underground natural gas storage reservoir



Underground hydrogen storage reservoir



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

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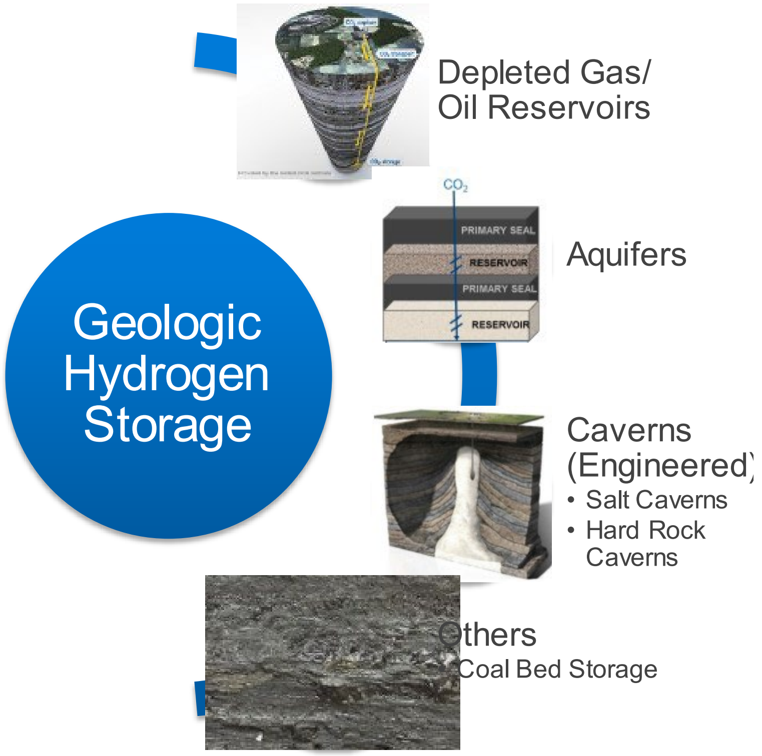
Potential Geologic Storage Options



		Salt Caverns	Hard Rock Caverns	Depleted oil and gas fields	Saline aquifers	Coal Bed Storage
General	Advantages	Relatively little cushion gas needed	Rapid cycling	Depleted fields are abundant	Saline aquifers are abundant	
	Disadvantages	High up front cost	Relatively small; likely need multiple caverns	Large cushion gas requirement	Exploration and apprasal needed; high cushion gas requirement	
Geological characteristics	Advantages	Proven hydrogen storage option; salt depositsare common globally; rapid cycling; ductile salt heals microfractures	Geomechanically stable; low cavern wall permeability; available outside sedimentary basins	Well understood geology	Well understood geology; lower seal integrity risk from existing penetrations	Adsorption may provide significant storage volume
	Disadvantages	Salt is geomechanically unstable	Subsurface characterization may be difficult	Potential for viscous fingering; interactions with residual hydrocarbons; seal integrity	Lack of existing geological characterization	Unknown behavior in subsurface; highly sensitive to stress state
Infrastructure	Advantages	Only 1 well needed for construction and operation	Only 1 well needed for injection/withdrawal	May be able to recycle existing infrastructure	Tailored infrastructure build-out	May be able to recycle existing infrastructure
	Disadvantages	May require pipelines for leaching water		Existing seal/reservoir penetrations add containment risk; may require multiple wells	No existing infrastructure; may require multiple wells	Existing seal/reservoir penetrations add containment risk; may require multiple wells
Costs		Moderate	High	Low	Low	Unknown
Experience with Storage		N_2, CH_4, CO_2, H_2	CH_4	CO_2, CH_4	CO_2, CH_4, town gas	CH_4

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Hydrogen Storage Experience in Salt Caverns since 1960s

Existing salt cavern hydrogen storage operations

	Teeside (UK)	Clemens (US)	Moss Bluff (US)	Spindletop (US)
Operator	Sabic Petroleum	ConocoPhilips	Praxair	Air Liquide
Hydrogen (H_2) end use	Power generation & transportation	Petrochemical & industrial	Petrochemical	Petrochemical
Commissioned (year)	1972	1983	2007	2017
Volume (m^3)/possible working gas capacity (10^3 t H_2)	210,000 / 0.83	580,000 / 2.56	566,000/ 3.72	906,000/ Information not available
Average depth (m)	365	1,000	1,200	1,340
Pressure range (bar)	56	70-137	55-152	68-202

(Adapted from Malachowska et al., 2022, https://doi.org/10.3390/en15145038).

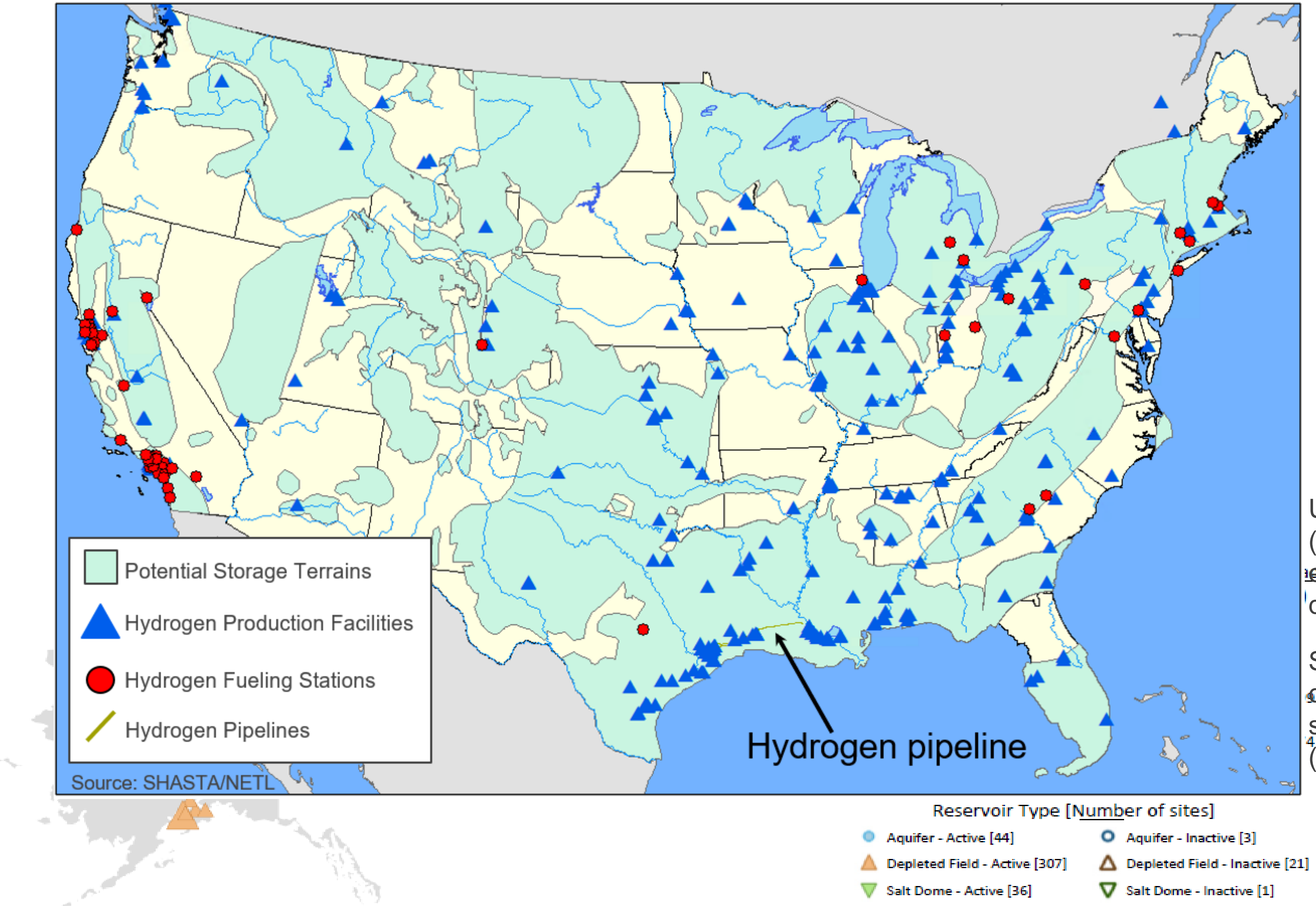
Limited Hydrogen Storage Experience in Porous Media

- Technical viability of hydrogen storage in these systems is relatively less developed due to few existing operations in comparison to salt caverns.
  - In comparison, 661 natural gas storage facilities were in operation worldwide at the end of 2019, with a combined working gas capacity of 422 billion m^3 with two thirds of the facilities concentrated in North America (Cedigaz, 2020)

- Several research programs have been undertaken over the last decade, primarily in Europe, dedicated to process understanding and computational modeling of hydrogen storage in geologic systems, such as HyUnder (Landinger et al., 2014), H2STORE (Pudlo et al., 2013), ANGUS+ (Kabuth et al., 2017), Underground Sun Storage (RAG, 2020) and SHASTA (Goodman Hanson et al., 2022) in the U.S.

Pore storage is most suitable for seasonal applications, with only a few cycles at relatively low production and injection rates.

Comparison of Natural Gas and Geologic H_2 Storage Resources in the U.S.



Underground Hydrogen Storage (UHS) potential and distance to existing hydrogen production and distribution infrastructure in the U.S.

Storage systems covered include depleted reservoirs, saline aquifers, salt caverns, and hard rock caverns (lined and unlined).

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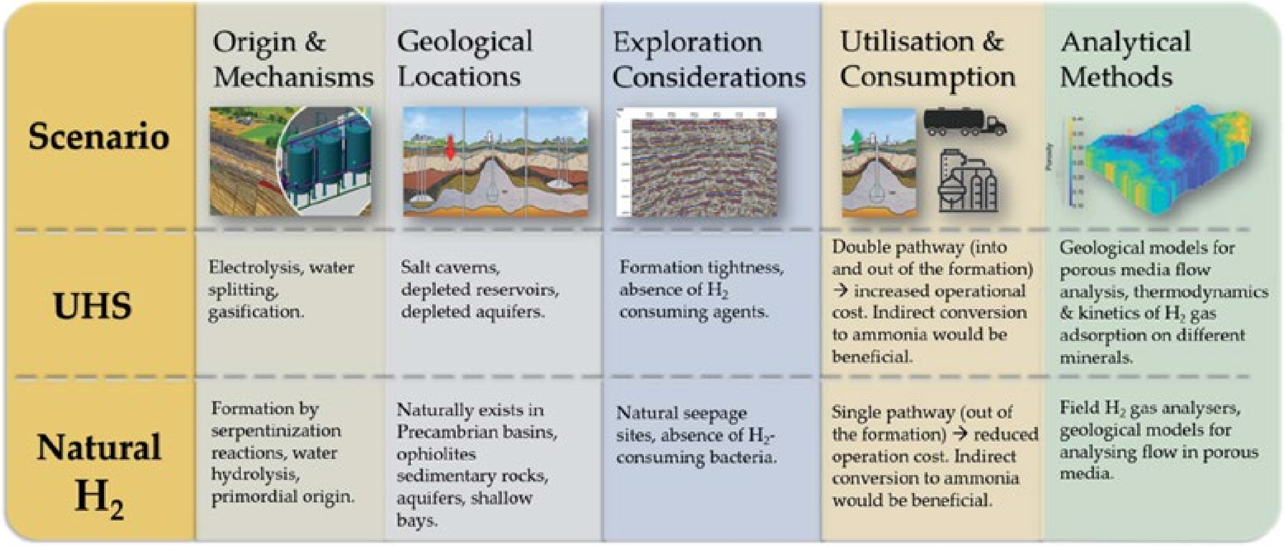
Naturally Occurring Hydrogen

- Presence of naturally occurring hydrogen is known for long time (vents etc.)
- Production potential highly uncertain
- Typically associated with mafic igneous and metamorphic rocks
  - deep resources (metamorphic core complexes)
  - too far offshore (mid ocean ridge basalt serpentinization)
- Current exploration focus on accumulations within onshore igneous or sedimentary reservoirs overlying failed rift systems and igneous intrusions



Scenario	Origin & Mechanisms	Geological Locations	Exploration Considerations	Utilisation & Consumption	Analytical Methods
UHS	Electrolysis, water splitting, gasification.	Salt caverns, depleted reservoirs, depleted aquifers.	Formation tightness, absence of H_2 consuming agents.	Double pathway (into and out of the formation) → increased operational cost. Indirect conversion to ammonia would be beneficial.	Geological models for porous media flow analysis, thermodynamics & kinetics of H_2 gas adsorption on different minerals.
Natural H_2	Formation by serpentinization reactions, water hydrolysis, primordial origin.	Naturally exists in Precambrian basins, ophiolites sedimentary rocks, aquifers, shallow bays.	Natural seepage sites, absence of H_2-consuming bacteria.	Single pathway (out of the formation) → reduced operation cost. Indirect conversion to ammonia would be beneficial.	Field H_2 gas analysers, geological models for analysing flow in porous media.

Comparison between naturally occurring hydrogen and UHS
[Epelle, 2022. https://doi.org/10.1039/D2SE00618A]

Naturally Occurring Hydrogen

Recent global efforts include:

- Resource estimation efforts by academics, geological surveys, and private exploration ventures for natural hydrogen accumulations.
- Efforts to develop hydrogen specific exploration strategies are in progress.
  - Largest recorded natural hydrogen flow was recorded in a well in Russia, flowing approximately 3.5 million cubic feet per day, which would provide the energy equivalent of just over 1 million cubic feet of natural gas per day, similar to a marginal natural gas well. This rate was sustained for less than three days before the well watered out and was shut in (Zgonnik, 2020).

Research and exploration efforts on natural H_2 reservoirs are valuable to inform technical considerations and risks associated with storage integrity for UHS in general.

Technical Considerations for Hydrogen in the Subsurface

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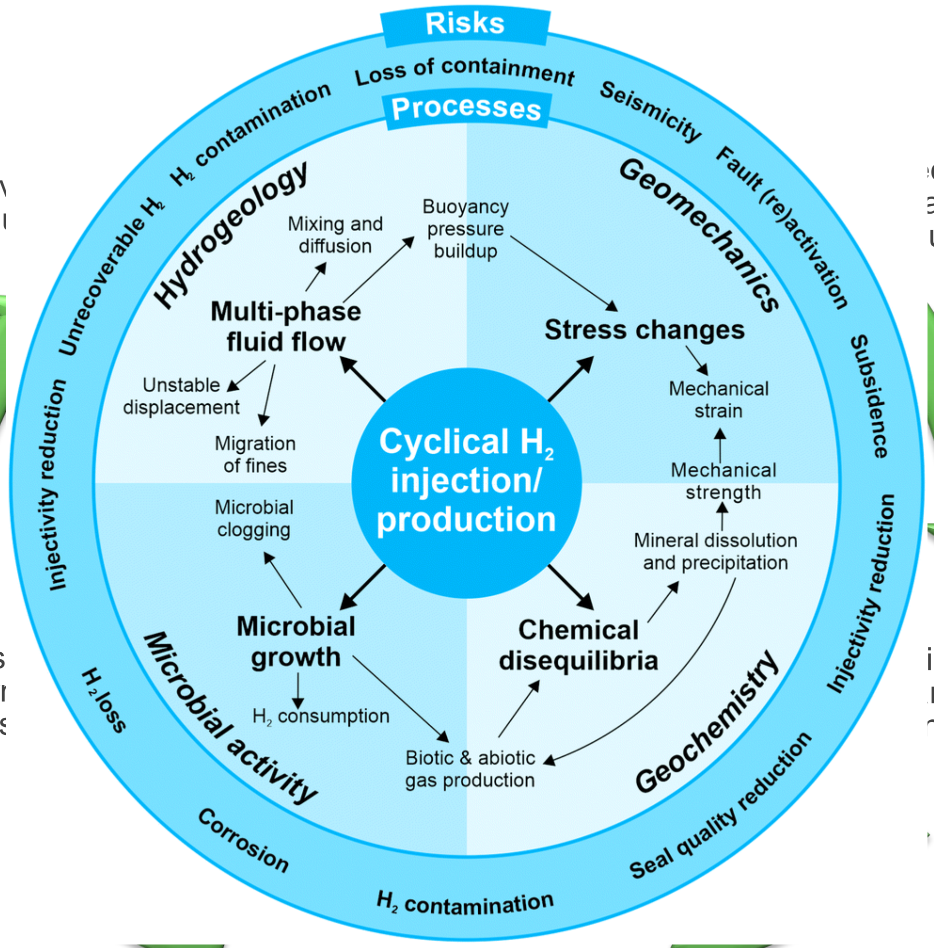


Engineered s
reservoir (Cavern
analysis

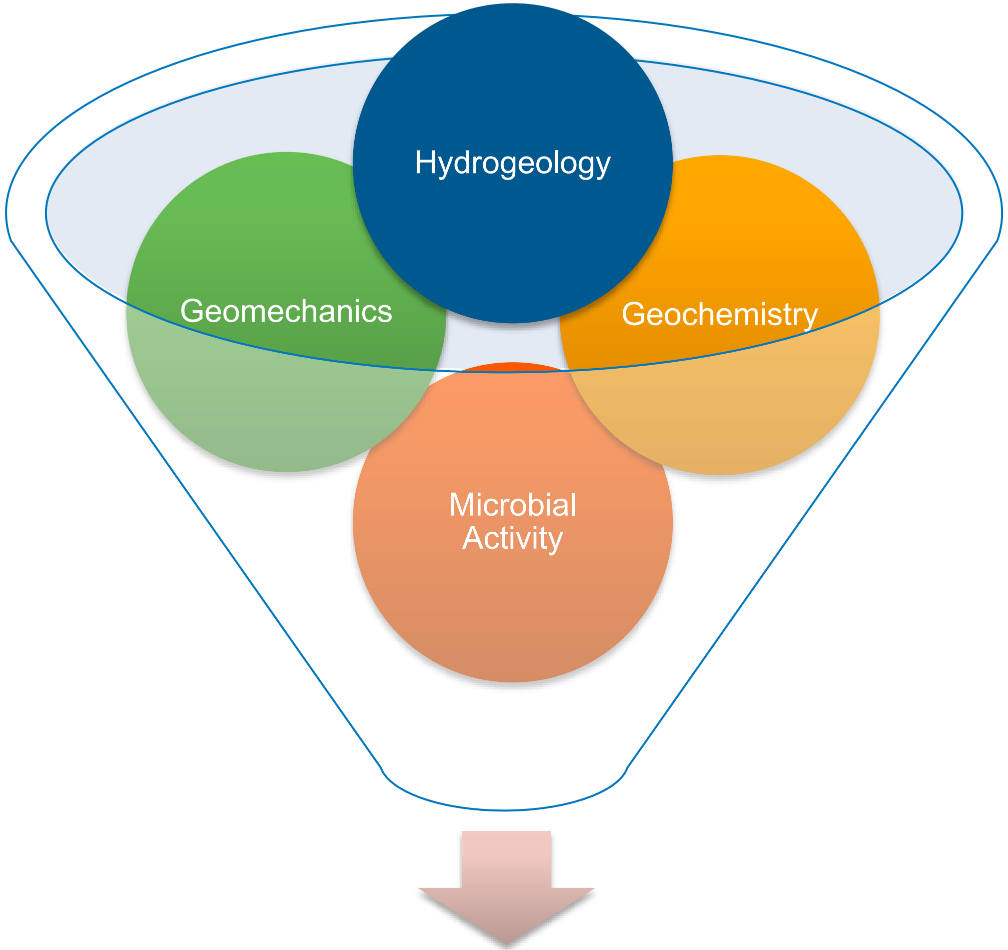
ing initial fill-up
nd cushion gas
needs

Heinemann et al., 2021
https://doi.org/10.1039/D0EE03536J

Control fluid upconing during
hydrogen production

Technical Considerations for Hydrogen in the Subsurface

Modeling UHS



Key Considerations for UHS Operations

Relevant Modeling Tools:
Eclipse, CMG-GEM, TOUGHx, GEOSx, COMSOL, GPSFLOW, PHAST, Ansys, etc.

Operational Performance Metrics

1. Total hydrogen capacity
2. Working gas capacity
3. Well deliverability
4. Diffusive losses
5. Chemical stability

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UHS Performance Assessment

UHS Performance in Depleted Gas Reservoirs

Preliminary Screening Performance Assessment Modeling Framework

Model Selection

Determine reservoir characteristics and assumptions for typical candidate gas fields to apply existing analytical correlations for hydrogen storage models in depleted gas reservoirs.

Demonstrate with natural gas fields in the U.S. Midwest region.

Implementation

Analytical modeling-based framework for rapid assessment of key UHS performance metrics such as hydrogen storage capacity, hydrogen loss via diffusion to the overlying caprock and the sustainable well operational capacity (i.e., well deliverability).

Comparison

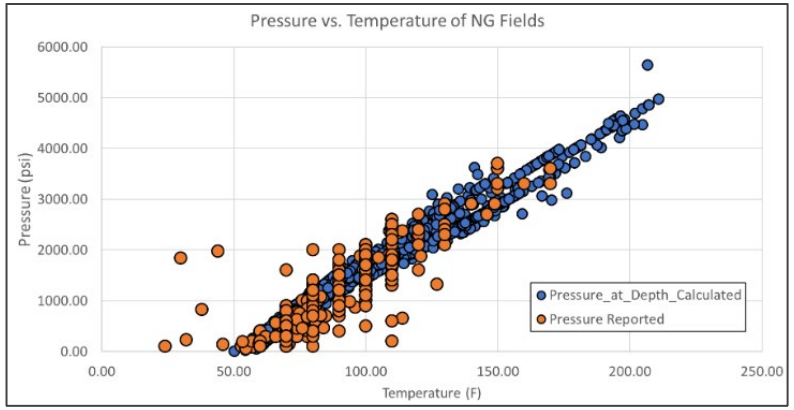
Facilitate understanding of dynamics in the subsurface by comparing hydrogen storage with familiar natural gas and CO_2 analogs in similar environments

UHS Performance in Depleted Gas Reservoirs

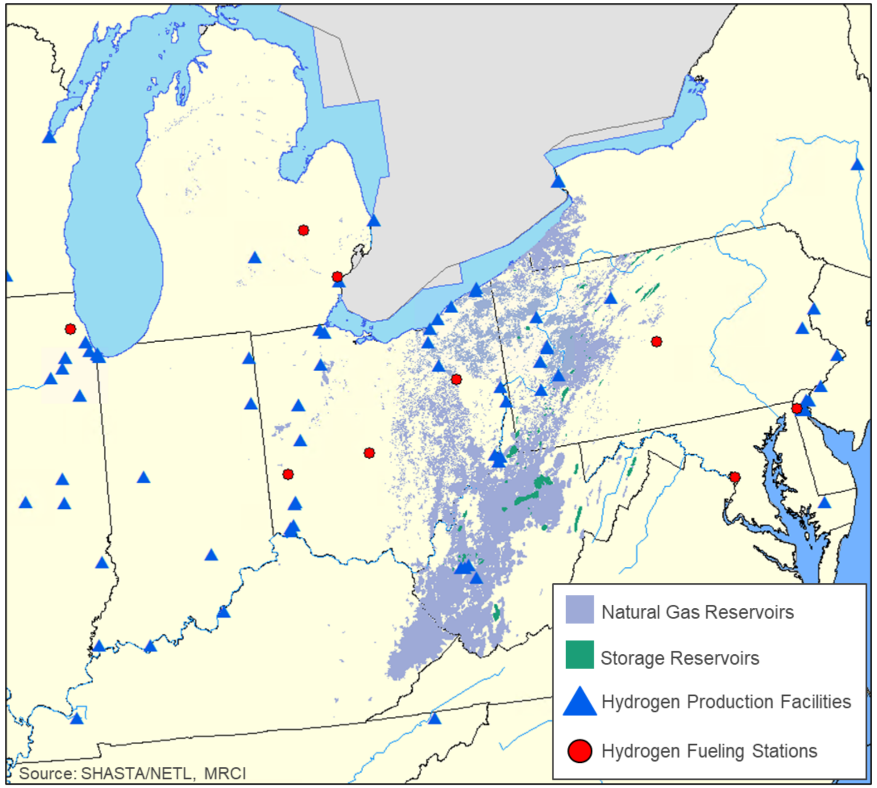
Preliminary Screening Performance Assessment Modeling

- This study captures 2063 unique gas fields (production and storage), some of which contain multiple reservoir units, with necessary reservoir properties for the modeling – depth, areal extent, thickness, and porosity.

- Data subset of petroleum reservoirs in the U.S. Midwest region compiled as part of the Midwest Regional Carbon Sequestration Partnership (MRCSP) (Lewis et al., 2021).

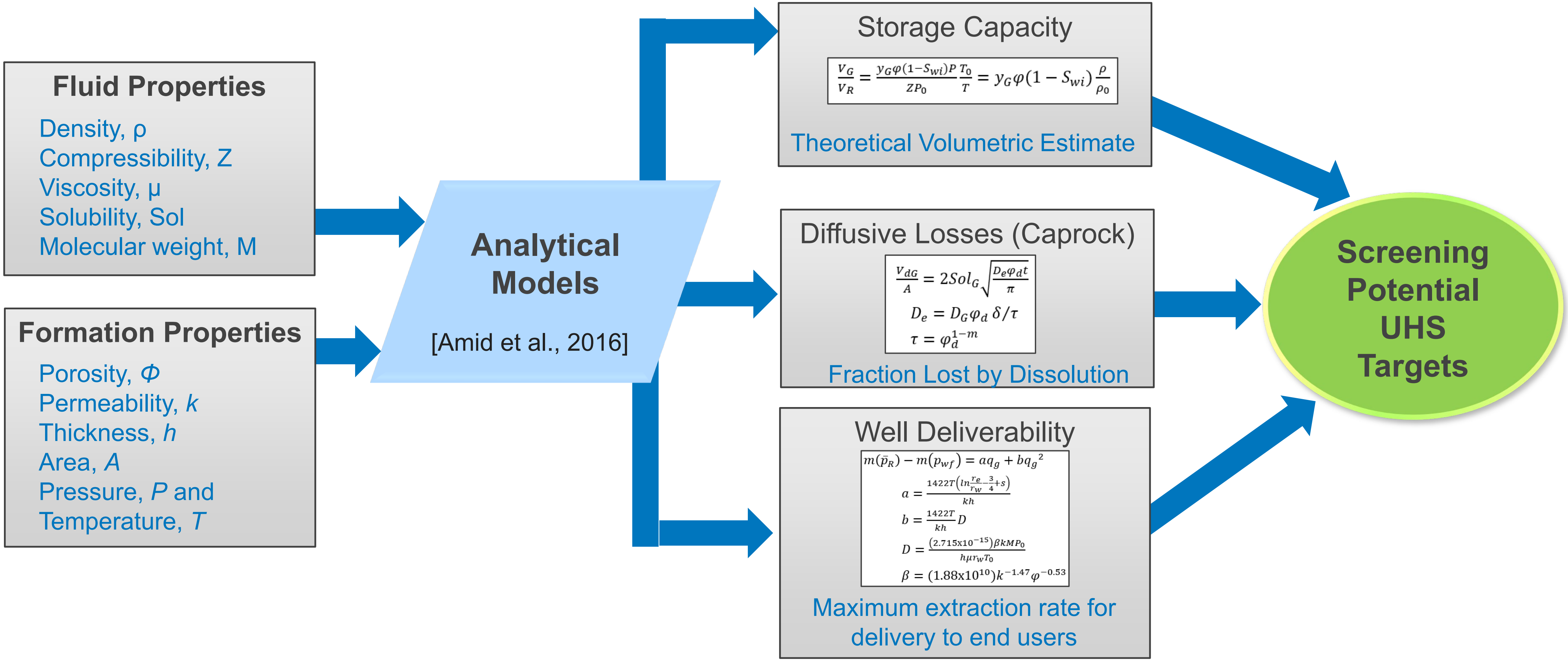


Data from extensive MRCSP Petroleum Fields database (Lewis et al., 2021).



UHS Performance in Depleted Gas Reservoirs

Preliminary Screening Performance Assessment Modeling



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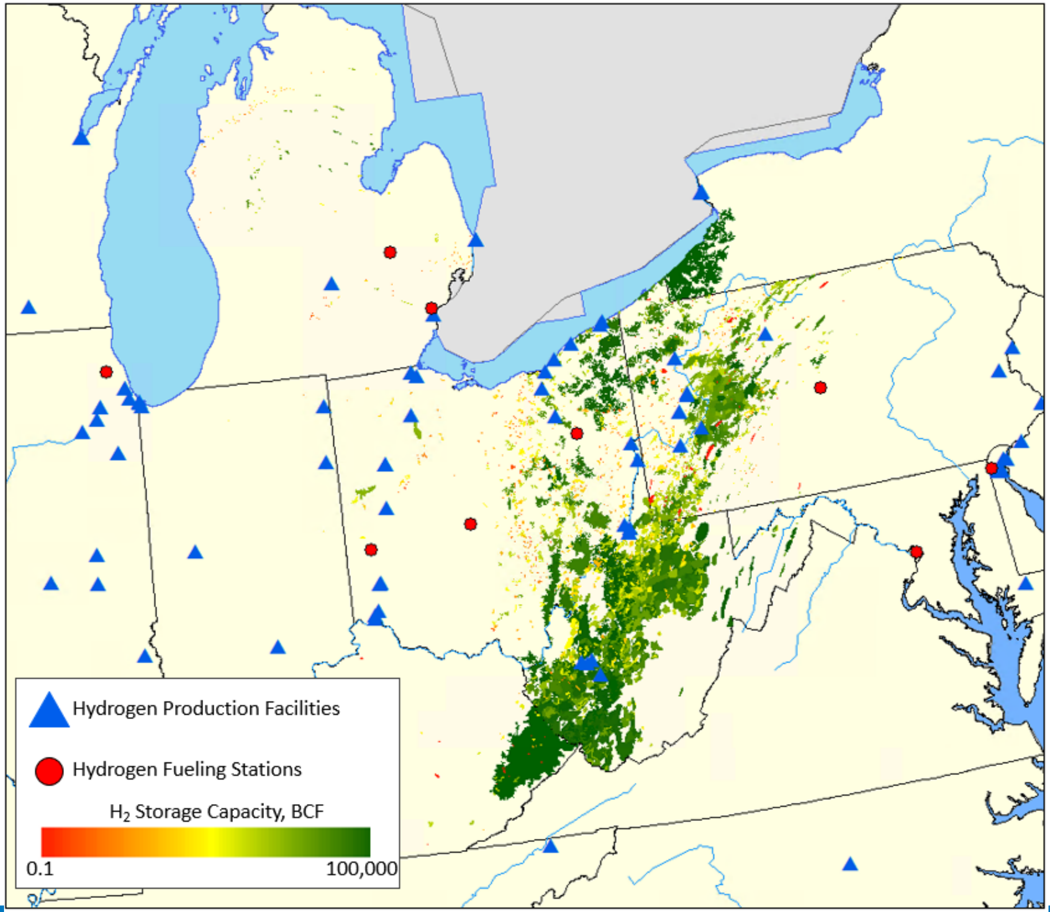
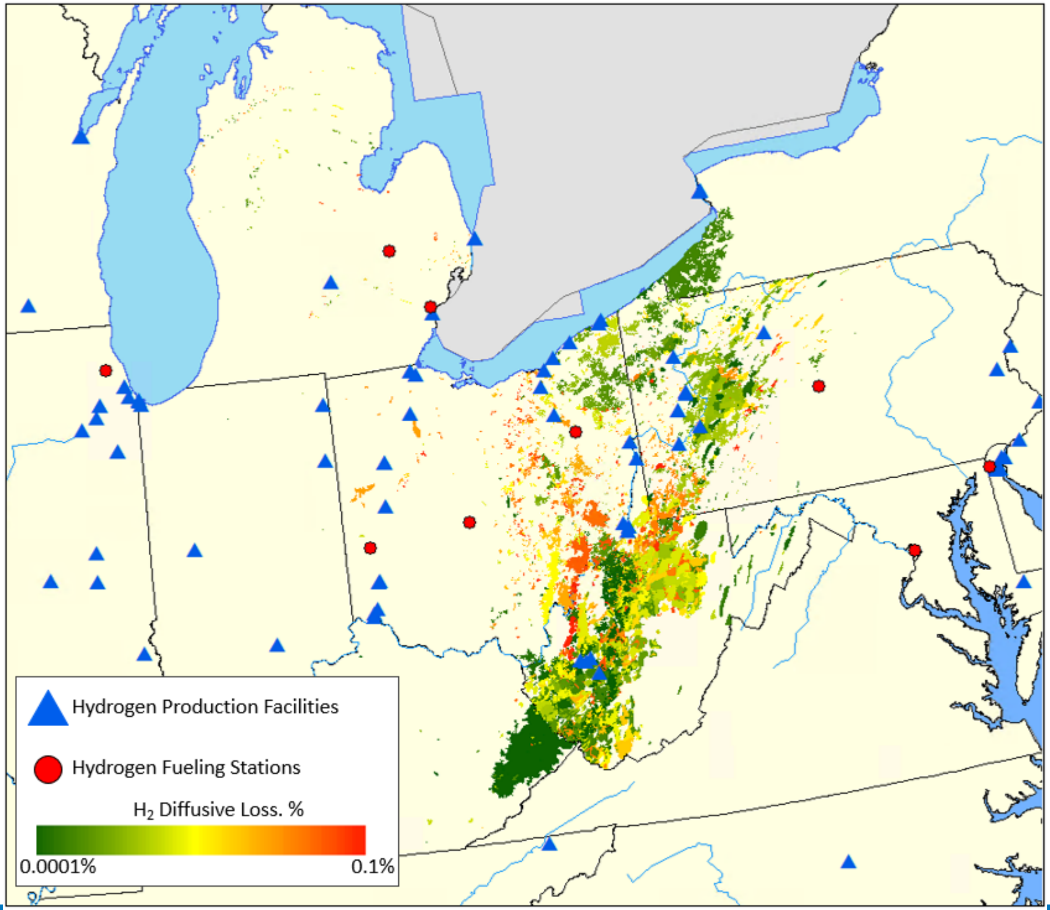
UHS Performance in Depleted Gas Reservoirs
Preliminary Screening Performance Assessment Implementation

Geographic distribution of storage capacity and diffusive loss metrics for the depleted gas fields considered.





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UHS Performance in Depleted Gas Reservoirs

Comparing Hydrogen Properties with Familiar Analog Storage Fluids

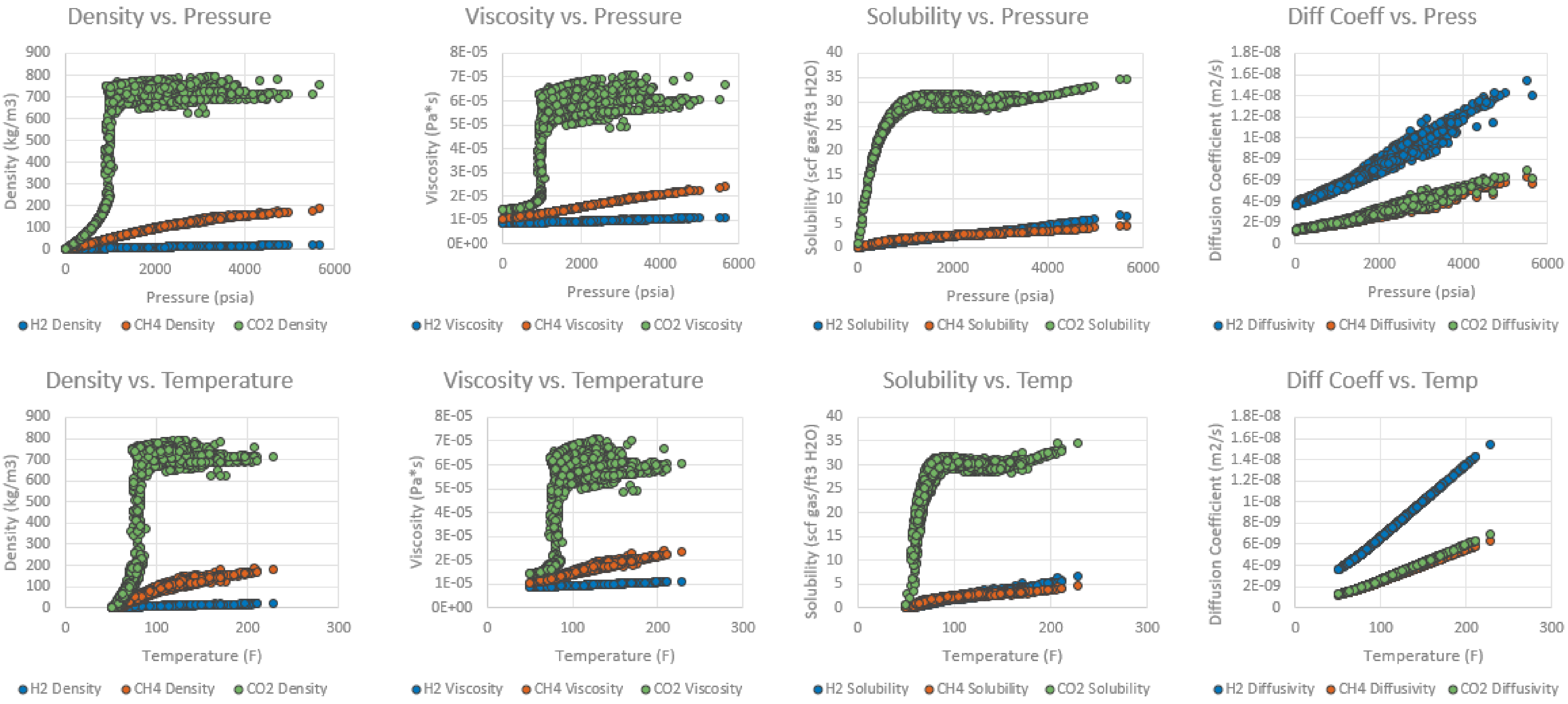


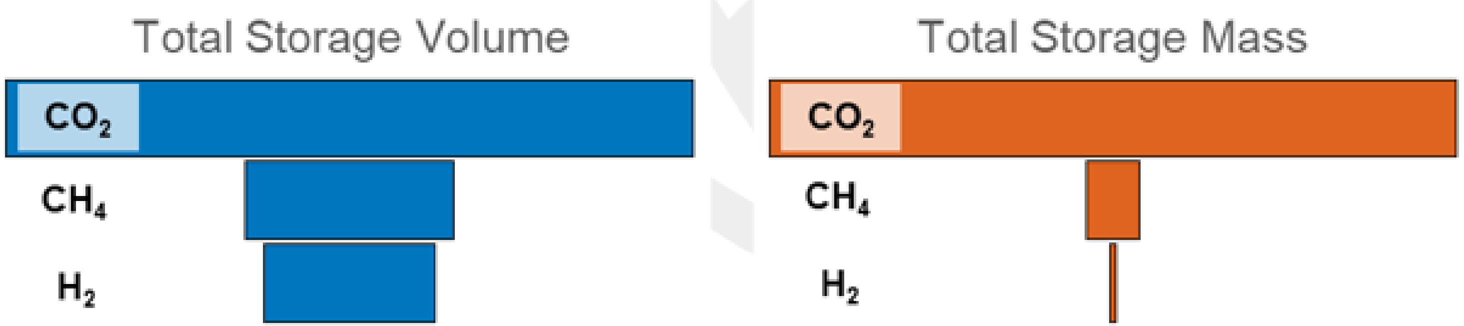
Figure 5-1: Thermophysical properties of pure hydrogen (blue), methane (red) and carbon dioxide (green) as a function of pressure (top) and temperature (bottom).

Comparison with Familiar Analog Storage Fluids

Geologic Storage Potential

Hydrogen has lower potential energy storage in a given reservoir when compared to natural gas and carbon dioxide.

Example showing relative comparison of the storage capacity in depleted gas fields in the U.S. Midwest for hydrogen, natural gas and carbon dioxide.



Volumes for methane and hydrogen are similar to one another, but the equivalent mass that can be stored is a full order of magnitude higher for methane than for hydrogen.

Comparison with Familiar Analog Storage Fluids

Storage Integrity and Infrastructure

- **Diffusive Losses:**

- The physical properties that influence diffusive losses are diffusivity and solubility. Given the difference in diffusivities between hydrogen and natural gas and their similar solubilities, diffusion appears to be significantly larger for CO_2 than for hydrogen due to its higher solubility.

- Given global CCS experience has sufficiently demonstrated caprock performance, this preliminary assessment thus indicates low risk of losses to diffusion of dissolved gas affecting caprock integrity for UHS.

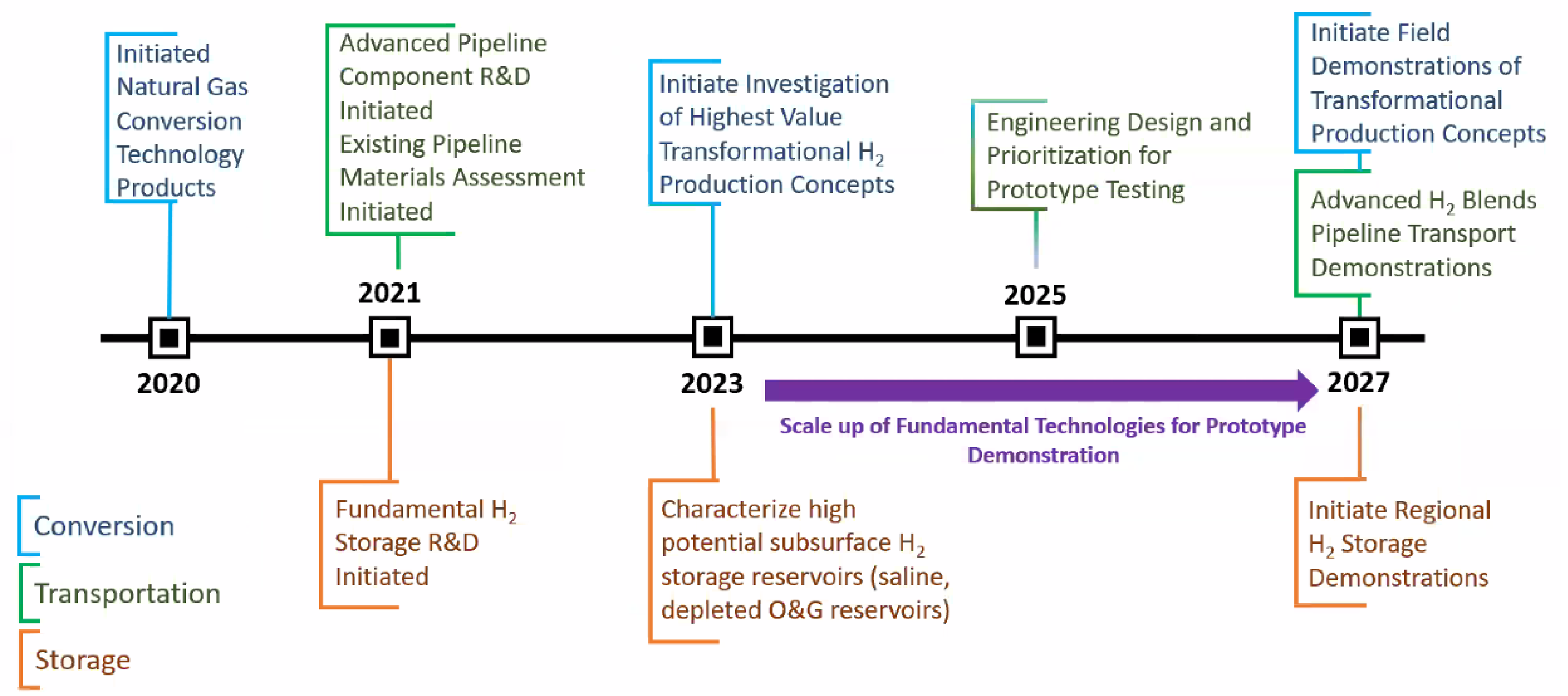
- **Deliverability Implications:**

- Accounting for the difference in energy densities, hydrogen pipelines will need to be equipped to transport much higher volumes of gas than are currently being transported in natural gas pipelines.

- UHS systems in comparison to natural gas storage will likely need
  - more wells per field or combined field operations to deliver the necessary quantities (by mass) of gas
  - higher operating pressure requirements than what is typically seen in natural gas.

Roadmap for Commercial UHS

Hydrogen Production, Transportation, and Storage Timeline

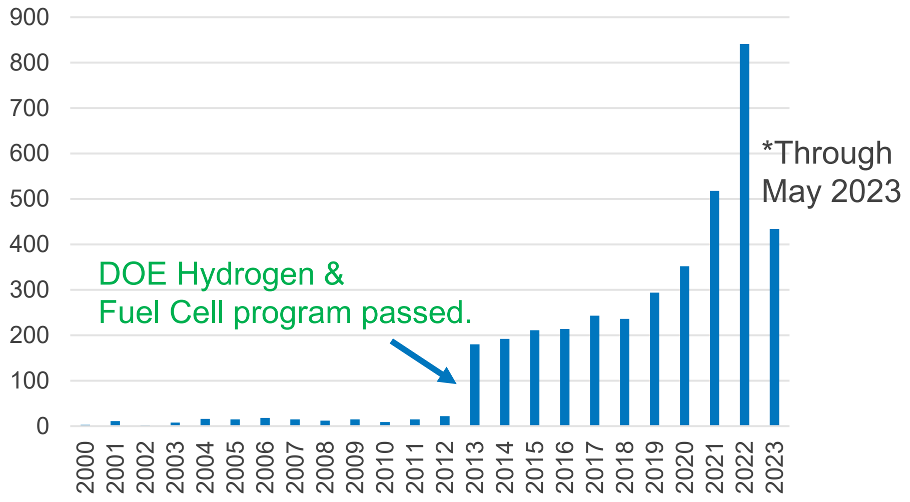


[U.S. DOE Fossil Energy and Carbon Management]

State-of-Current Understanding on Hydrogen

- Most aspects of the science of generating, capturing, transporting, and storing hydrogen are well studied.
- Publications discussing UHS and related technologies have been increasing significantly since 2013, but gaps remain in our understanding of subsurface dynamics of hydrogen and regulatory systems within the U.S.

H_2 PUBLICATIONS PER YEAR



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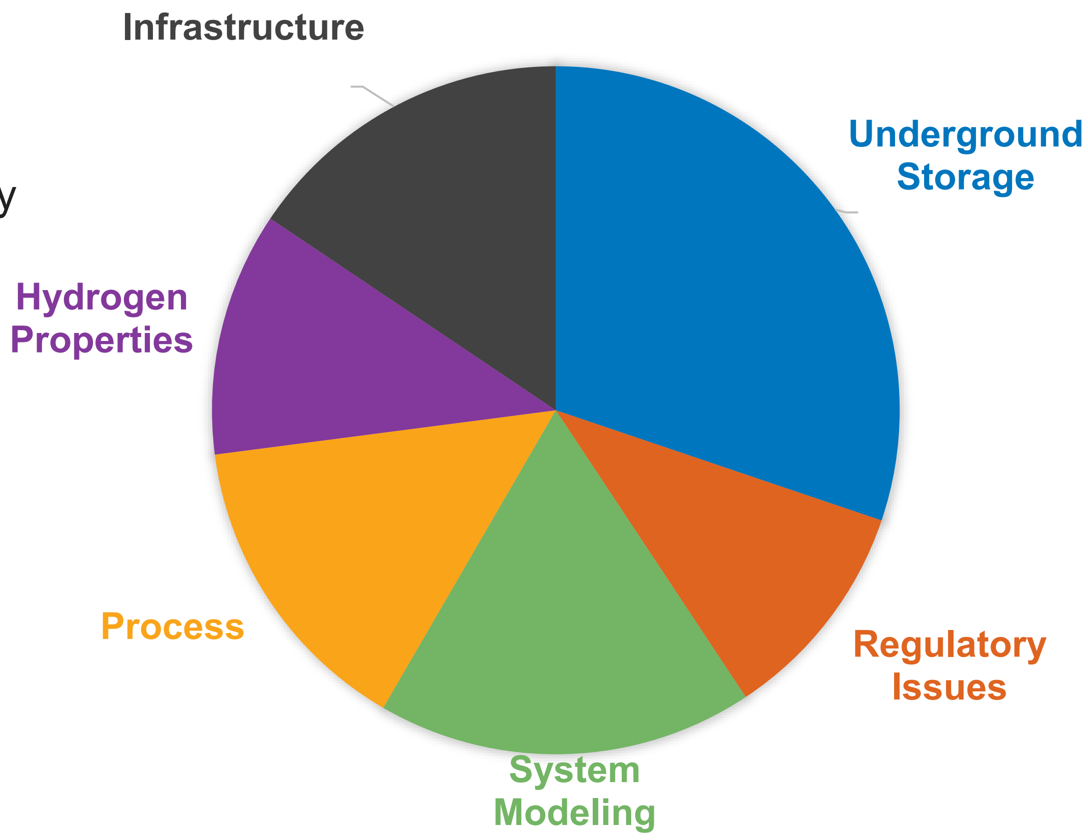
LITERATURE TOPICS



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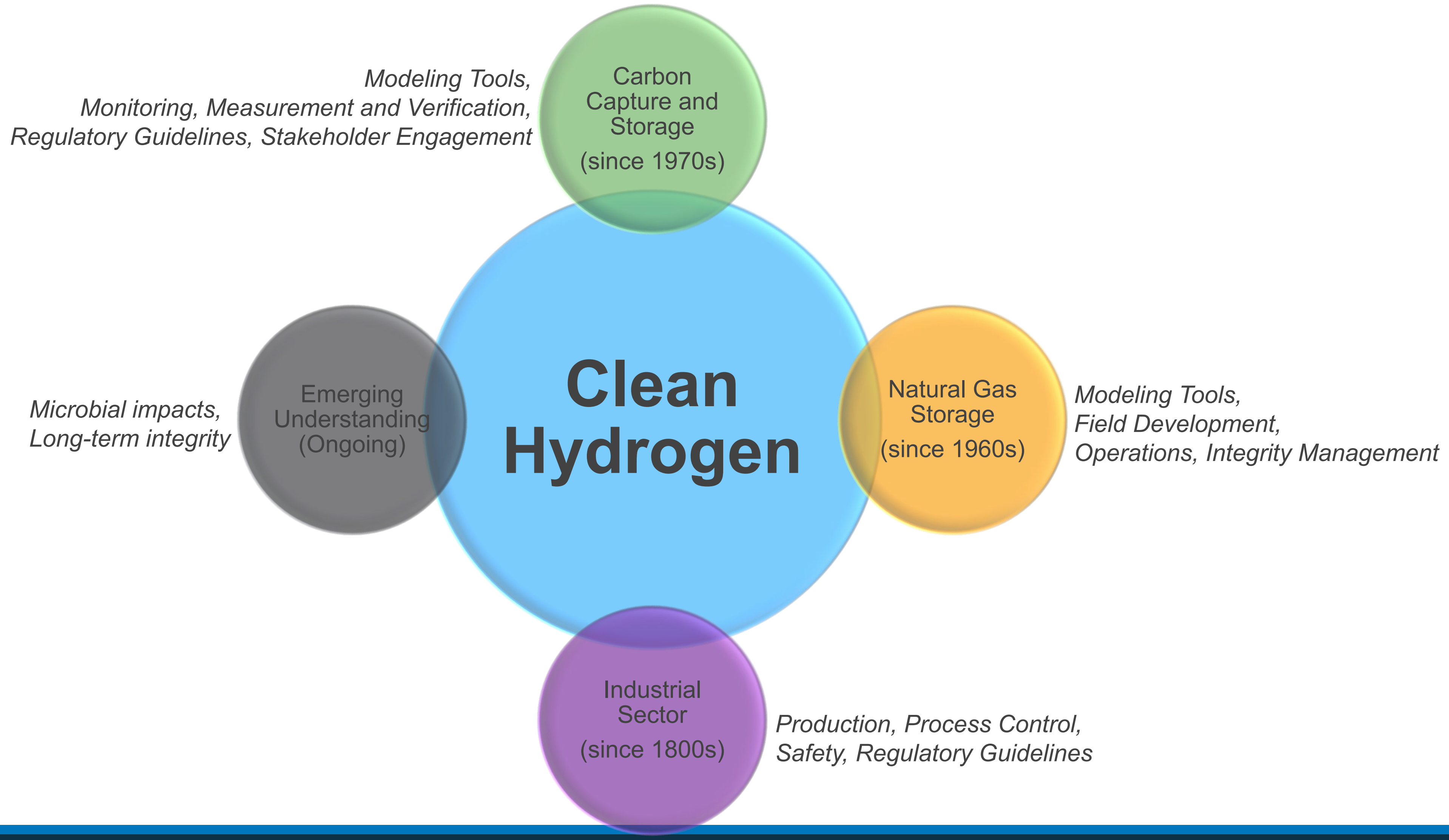
Leveraging Lessons Learned from Analog Industries



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Monitoring Considerations for UHS

Building Upon Existing CCS and Industrial Lessons Learned

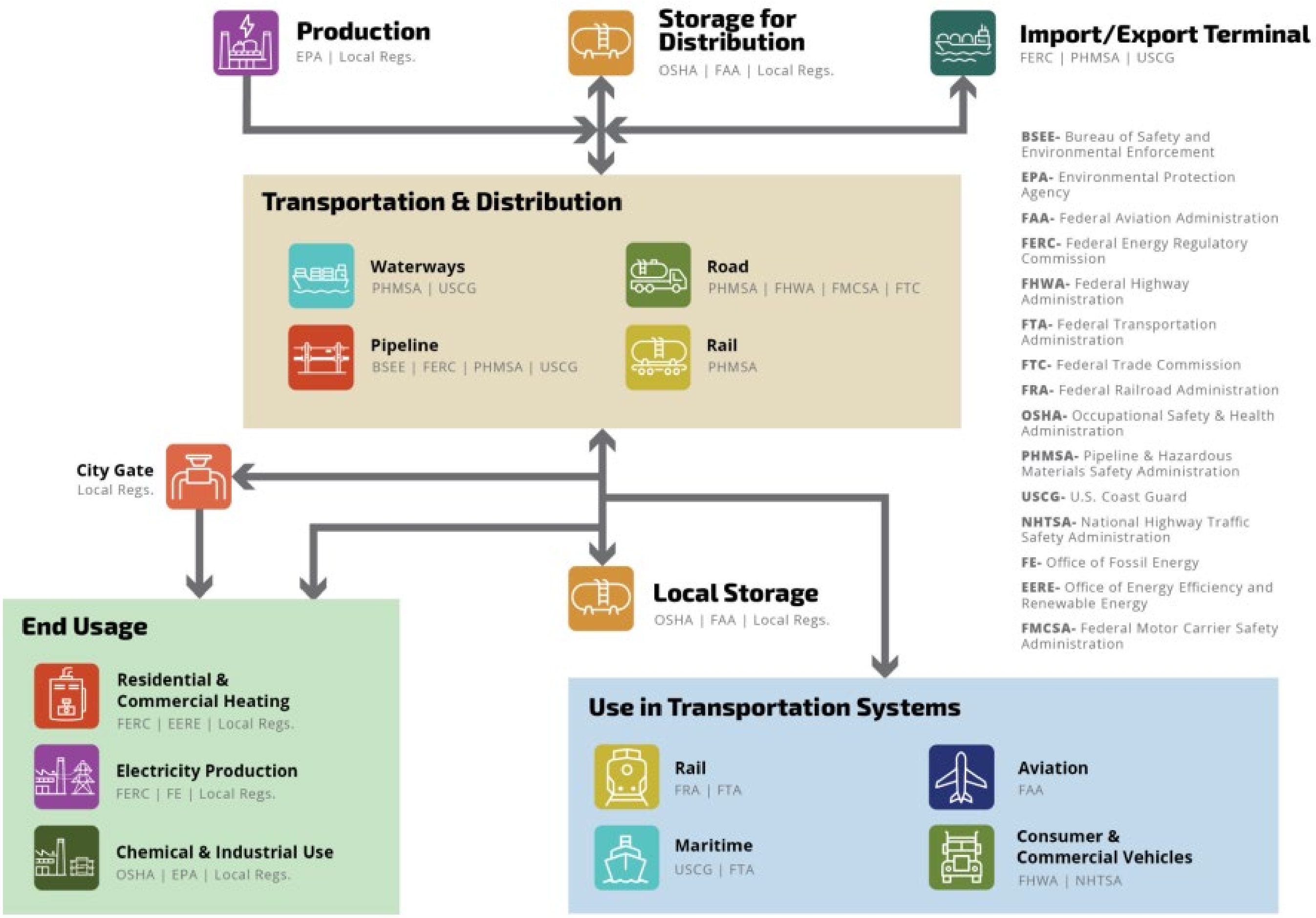
- Relevant testing and monitoring technologies to monitor the integrity of the injection/ production wells, groundwater quality, and tracking hydrogen and pressures throughout the life of the project.
  - Seismic monitoring and risk management experience in the oil and natural gas, wastewater disposal, and CCS industries can be applied.
  - Above-zone pressure monitoring (AZMI) adapted from CCS industry can be used for surveillance and demonstrate storage integrity.
  - Monitoring groundwater quality to identify geochemical changes that may be required to prevent groundwater contamination.
- Hydrogen leak detection in large-scale storage facilities requires wide-area, real-time monitoring.
  - Emerging areas of research include advanced materials, and application of optical fiber sensors and passive wireless sensors. Wide array of existing commercial hydrogen sensor technologies available for surface facilities.

Regulatory Readiness for Hydrogen

Building Upon Extensive Industrial Experience

- Sandia National Laboratories compiled "Overview of Federal Regulations for Hydrogen Technologies in the U.S." to identify
  - regulators and agencies that need to be engaged by stakeholders for future systems
  - limits of federal oversight (I.e., state/local jurisdiction rather than federal)
- Each portion of the hydrogen supply infrastructure is regulated by international, federal, state, and local entities.
- Interactions between federal and local regulations should become clearer over the next several years.

Regulating entities for the hydrogen supply value chain

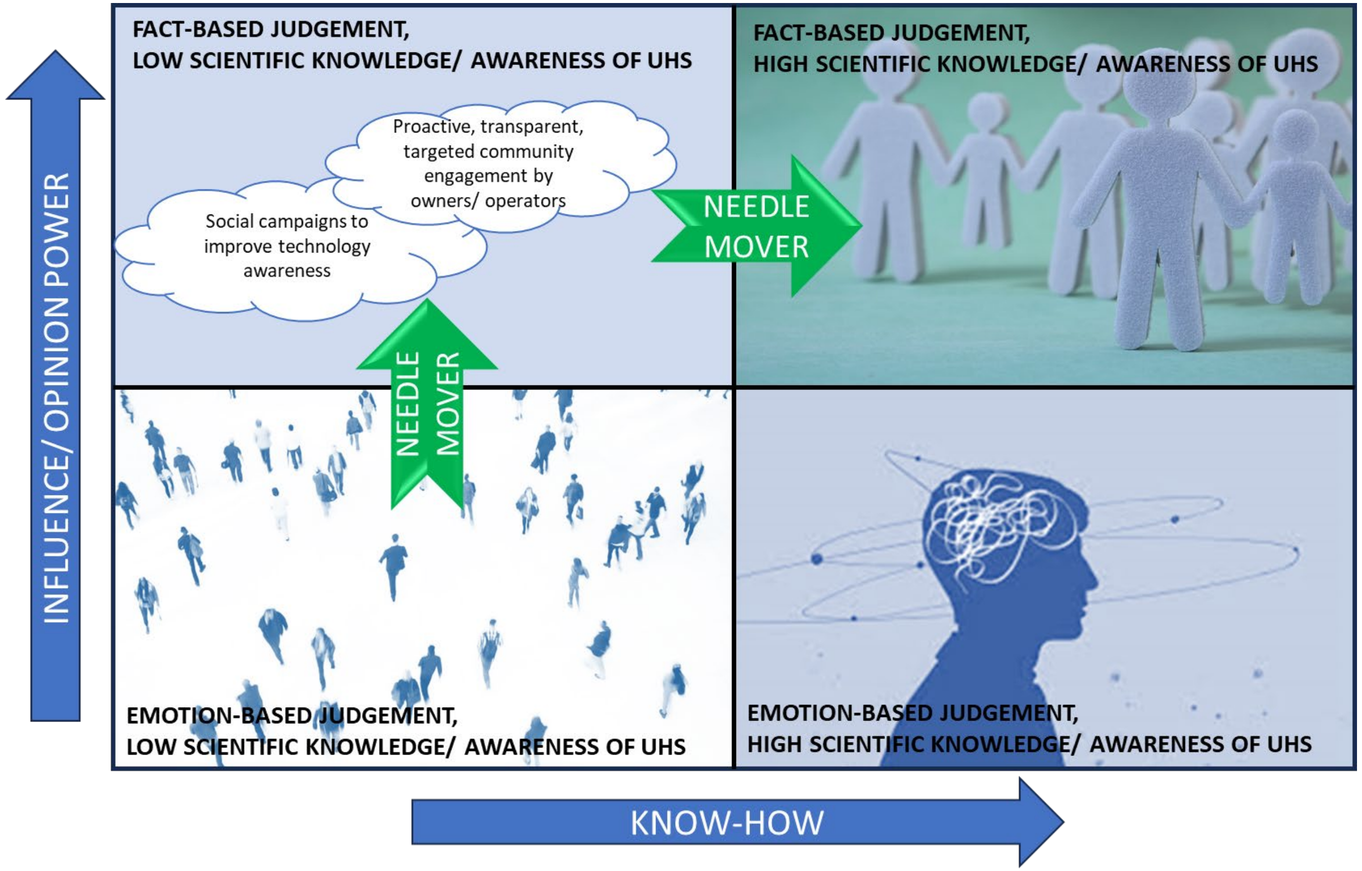


Source: Baird et al.,2021. Federal Oversight of Hydrogen Systems.

Societal Considerations

- Limited public understanding of hydrogen technologies
- Key concerns:
  - Implementation and safety related to hydrogen handling
  - Perception of the cost to transition from natural gas to hydrogen for both industrial and individual (home or auto) use.
- Stakeholder engagement frameworks and lessons learnt from CCUS industry could be valuable
- CBP plans mandated for federal funding

Framework for shift in public perception towards acceptance of hydrogen technologies and underground hydrogen storage



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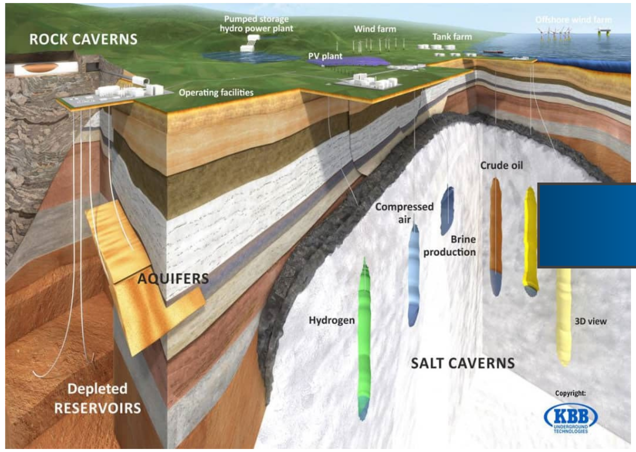
Roadmap for Accelerating Hydrogen Readiness

De-risk storage options



Build transportation network

Reconcile end uses

Understand community impact

Conduct community outreach

Build community partnerships

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Summary

- Many aspects with industrial experience across decades, even centuries
- Some new aspects associated with large-scale implementation
  - Current hydrogen storage mostly above ground. Subsurface storage is limited but expected to become dominant if implementation of a ‘hydrogen economy’ succeeds.
  - Depleted reservoirs offer significantly higher storage potential and are even more broadly available than salt terrains that are currently viewed as the lowest-risk option, with low cost to deliver, high probability of operational success.
  - Important to reconcile use considerations and transportation simultaneously with de-risking reservoir development, as all three aspects must be in place for success.
- Hydrogen Hub efforts enabling hydrogen readiness to meet domestic decarbonatization goals
  - Hubs implemented globally mostly green but blue hydrogen also important and relevant bridge to sustainable options.

Thank you!

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It can be done

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