PNNL-35719

Enhancing Site Screening for Underground Hydrogen Storage: Qualitative Site Quality Assessment

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

March 2024

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

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Executive Summary

The global transition toward renewable energy sources is important to mitigate fossil fuel dependency and achieve carbon emission targets by 2050. This shift has underscored the importance of innovative solutions to address large-scale storage of decarbonized energy and balance supply of environmentally friendly energy with demand. Underground hydrogen storage (UHS) has emerged as a promising strategy to store renewable or decarbonized energy in subsurface formations for future retrieval and use. This report focuses on enhancing the site screening process for UHS facilities.

Building on insights from prior research to identify key criteria influencing site suitability, we develop a comprehensive set of 15 specific criteria essential for refining the selection of UHS sites. These criteria inform various aspects of UHS feasibility, such as reservoir performance, legal access, regulatory compliance, economic viability, public acceptance, and safety and security considerations. We provide context and benchmark values for data that is pertinent to these considerations and suggest avenues for assessing these considerations on a site-screening scale. Then, we integrate these considerations into a qualitative framework that potential site operators can use to identify ideal UHS locations. Our proposed methodology aids in the evaluation of potential UHS sites by establishing a simple qualitative framework that offers broad insights into site suitability from individual factors.

Our approach is designed as a flexible guiding framework rather than a rigid template for site screening, emphasizing the importance of customizing approaches to individual circumstances. As a UHS site development project evolves, adapting more comprehensive and tailored selection criteria and methodologies that integrate holistic evaluations will be essential for efficient and effective site screening processes tailored to specific project requirements, ensuring the success of UHS operations.

This report provides potential stakeholders, such as developers and regulators, with a broad understanding of the important considerations for UHS, benchmark values and/or context for these considerations, and guidelines on how to use these considerations to turn a UHS concept into an actionable project. By addressing these critical elements, the report equips potential UHS stakeholders with the knowledge and tools they need to make informed decisions and take the right first steps in developing safe, effective, and viable underwater hydrogen storage solutions.

Acknowledgments

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Acronyms and Abbreviations

HIFLD	Homeland Infrastructure Foundation-Level Data
SHASTA	Subsurface Hydrogen Assessment, Storage, and Technology Acceleration
TDS	total dissolved solids
UGS	underground gas storage
UHS	underground hydrogen storage
UNGS	underground natural gas storage
USDW	underground source of drinking water
USGS	U.S. Geological Survey

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1.0 Introduction

A global shift toward sustainable and clean energy sources is a critical response to achieving carbon emission reduction targets by 2050.[1] Currently, carbon-intensive fuels such as hydrocarbons predominantly fuel electricity generation, transportation, and industrial operations. To mitigate carbon emissions from these sectors, electricity generated from renewable sources like solar radiation and wind offers a sustainable solution. However, these renewable sources are not without their challenges. Seasonal variability in electricity production and consumption patterns leads to an imbalance between supply and demand.[2] For instance, wind speeds and solar irradiance fluctuate throughout the year, resulting in inconsistent electricity generation, whereas seasonal shifts in electricity consumption contribute to the supply-demand mismatch (Figure 1). Further, certain energy-intensive applications such as long-distance shipping and industrial processes pose significant challenges for electrification.[3] Emerging technologies must surmount these obstacles to pave the way for a decarbonized future.

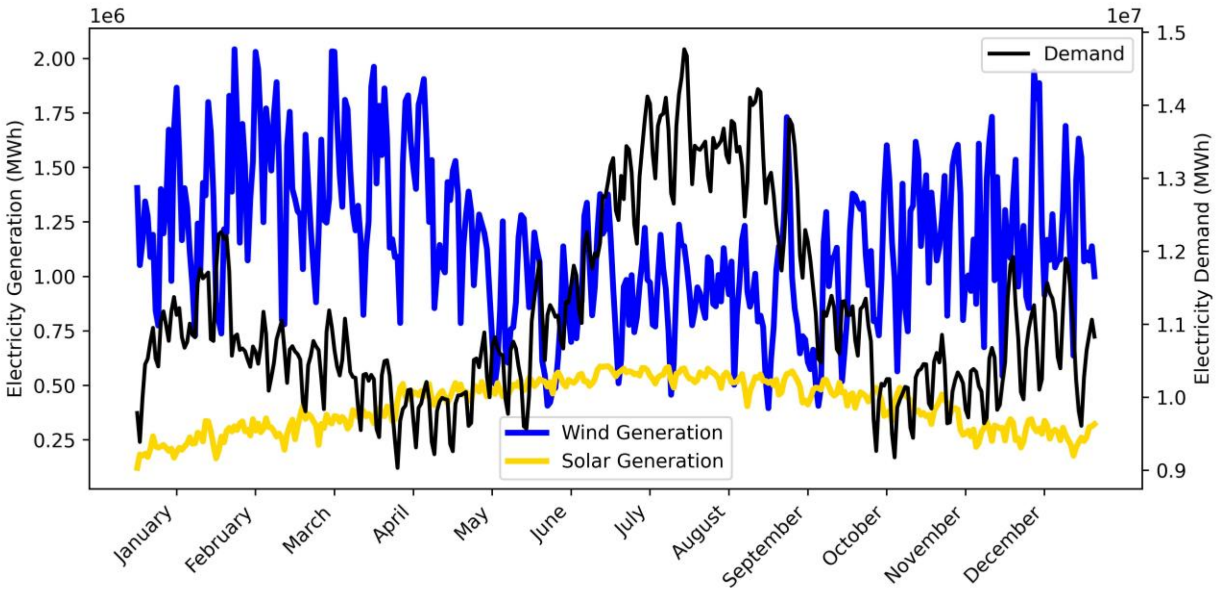

Figure 1. Averaged electricity generation and demand in the contiguous United States, 2023-2024.[4] Left y-axis: wind and solar energy generation; Right y-axis: electricity demand.

Hydrogen gas presents a promising solution. It can be produced through methane reformation, electrolysis, or alternative methods. When combusted, hydrogen produces no carbon emissions, making it a versatile energy source for electricity generation, transportation, or industrial processes.[3] Utilizing hydrogen generation powered by renewable sources or incorporating carbon capture technologies can significantly contribute to decarbonizing global energy systems. However, to meet the demands of electricity generation and industrial applications effectively, a reliable and controllable supply of hydrogen is essential. Thus, use of hydrogen generated from variable renewable power sources (Figure 1) requires the implementation of large-scale hydrogen storage solutions.

Underground hydrogen storage (UHS) has emerged as a promising solution to address the issue.[2, 5] Drawing inspiration from the established practice of underground natural gas storage (UNGS), UHS involves the large-scale storage of hydrogen, produced from excess renewable energy, within subsurface formations, to be retrieved as needed. Hydrogen, which has a high volume to mass ratio (i.e., low density) and high mobility, presents storage challenges that can be mitigated by using the natural compression and containment provided by deep subsurface conditions. This approach reduces the necessity for extensive surface storage tanks.

UHS can be implemented in two main types of geological formations[1]: (1) artificial structures such as salt caverns, which are engineered to deliver gas efficiently during periods of high demand,[6] and (2) natural porous media, including depleted oil and gas reservoirs and saline aquifers. While artificial structures offer more control and predictability, their suitability is limited to specific locations. In contrast, natural porous media are more widespread and typically offer greater storage capacity.

The process of site screening and prioritization is a critical and challenging initial step in the development of UHS facilities. Several studies[7-9] have identified potential sites, among a larger pool, that are relatively favorable for hydrogen storage by assessing various criteria that could influence the success of such operations. These criteria encompass physical attributes (e.g., porosity, permeability, depth, temperature, pressure, trap structure), chemical factors (e.g., rock and water chemistry), operational aspects (e.g., deliverability), and logistical considerations (e.g., distances to population centers, energy generation) of the potential storage locations. Other studies investigate the relative weight of these criteria to enhance site screening processes.[10-13] While prior research has predominantly focused on assessing and ranking potential sites based on various attributes and is useful for informing important criteria and understanding their respective importance in the selection of hydrogen storage sites, these methodologies have limitations: They often isolate interdependent factors, not accounting for the relative significance of each factor, and may overfit available data specific to their study region. Establishing a universal screening framework is challenging due to substantial variations in the available data and specific use cases.[14] There is yet to be a site screening framework that integrates physical, chemical, operational, and logistical considerations to arrive at a holistic and adaptable screening process.

In this report, we aim to outline essential criteria for evaluating potential hydrogen storage sites; establish benchmarks for these criteria, where data permits, to enable stakeholders to compare options within a broader dataset; and propose methodologies for assessing each criterion on a site screening scale. Recognizing that early-stage site screening is inherently constrained by limited information, we introduce a set of broad yet critically important considerations that can be adapted based on available information. These considerations are designed to facilitate a qualitative evaluation of a site's suitability for UHS, thereby laying the groundwork for a more informed selection process in the characterization and performance assessment stages. As more data becomes available in the later stages of site selection, we advocate for transitioning toward a more quantitative methodology. This evolving approach should adapt to the increasing availability of detailed site data, integrating comprehensive factors such as reservoir performance evaluations and economic assessments alongside site-specific use cases. By drawing on the principles shared with underground gas storage (UGS) and geological carbon storage, we leverage insights from the existing body of literature in these related domains to inform and refine our approach to site screening for UHS.

This report is highly relevant for potential stakeholders in UHS, including developers interested in investing in and constructing UHS facilities, as well as regulators responsible for overseeing and approving UHS projects. By using this report, these stakeholders will gain valuable insights that can inform their decision-making and actions. Specifically, the report will equip them with the knowledge to understand the key data they need to collect and consider when developing UHS projects, evaluate how their potential geologic storage opportunities compare to other storage options available nationwide, and identify the most promising storage opportunities from a larger pool of options for further investigation and development. Ultimately, this report provides potential underground hydrogen storage stakeholders with the necessary information to make informed decisions and take the appropriate first steps in transforming a UHS concept into a viable, actionable project.

2.0 Site Selection of UHS

UHS site selection involves four distinct stages: screening, characterization, performance evaluation, and final selection (Figure 2). Broadly, site selection guides a potential UHS operation from an idea at a regional scale to a development at a specific site. In the initial stage of site selection, screening leverages existing basin, regional, and site-scale data to narrow down numerous potential storage sites to a manageable number. Subsequently, these sites undergo comprehensive characterization, where new data is gathered to complement existing information and address knowledge gaps.

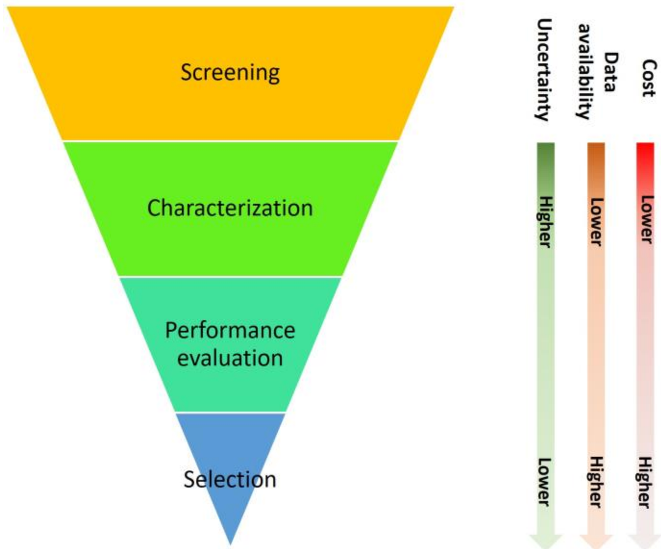

Figure 2. Site selection process for underground hydrogen storage (modified from Callas et al.[15]).

Site characterization unfolds as a continuous and iterative process, typically beginning with the collection and evaluation of more data for the sites identified by the screening stage. It progresses to include the acquisition of new data, covering various aspects like geology, rock properties, hydrogeology and geothermics, fault and fracture characteristics, in situ conditions, composition and phase behavior of native fluids and injected hydrogen streams, reservoir history for hydrocarbon reservoirs, history of wells and their condition, and land features. This process incurs growing costs as the assessment scale is refined from regional to site specific, increasing resolution and certainty. Performance evaluation essentially relies on both geomodeling and dynamic reservoir modeling that consider coupled hydrodynamic, thermal, geochemical, geomechanical, and geophysical processes alongside detailed geological settings. This holistic evaluation enables an understanding of the combined impact of different components under various scenarios. Ultimately, final site selection depends on the outcomes of performance evaluation, considering non-technical factors such as economic, legal, and societal factors, aligned with specific business use cases. Once performance evaluation confirms a potential storage site's capability to meet the required hydrogen storage demand, development can commence at the chosen site, thereby completing the site selection process.

This report primarily focuses on screening within the broader site selection process, providing a comprehensive overview of essential considerations without a precisely defined use case. The information presented here serves as guidance rather than a one-size-fits-all approach for site screening, emphasizing the need for tailoring to specific geological, geographic, jurisdictional, and societal conditions. The scope of this report is limited to porous media reservoir sites, excluding chamber reservoirs like salt domes and salt caverns.

3.0 Site Screening of UHS

The site screening criteria should inform various aspects of a site for UHS and can be categorized as shown in Figure 3.

Figure 3. Aspects of consideration for site screening.[14]

The initial stage of the site screening process involves elimination, wherein candidate sites are removed from consideration. This stage comprises critical criteria, which are mandatory for consideration and could make a hydrogen storage project exceedingly difficult or implausible. Subsequently, additional screening criteria are applied to assess sites that pass the elimination stage, identifying more favorable sites for further investigation and investment. This stage comprises preference-based, or desirable, criteria, which are used to assess whether sites exhibit preferred or unfavored conditions relative to one another. While this does not eliminate sites outright, sites with numerous unfavorable conditions may be removed from consideration. Finally, sites that meet the critical criteria and exhibit more preferrable criteria than their counterparts will advance to the next stage of site selection: characterization. This framework builds on the approach from the IEA Greenhouse Gas R&D Programme.[14] Detailed criteria are proposed in Table 1 and discussed in the sections that follow.

Table 1. Site screening criteria for UHS.

Criterion Level	Criterion	Eliminatory or unfavored	Preferred or favorable	Classification
Critical	Containment	Low	High	Reservoir performance Safety and security of storage Economics
	Potential to affect USDW	High	Low	Safety and security of storage Legal access and regulatory permission
	Legal accessibility and availability	Located in a protected (e.g., national monument) or preserved area, no right of access, no chance to own pore space	Unprotected or unreserved area, accessible, and with a chance to own pore space	Legal access and regulatory permission
Desirable	Faulting and fracturing intensity	Extensive	Limited to moderate	Safety and security of storage
	Potential for natural or induced seismicity	High	Low	Safety and security of storage
	Socioeconomic accessibility and availability	A site, such as a hydrocarbon reservoir, still in production or with third-party equity interests; a site located in a high-density population area such as a city	Not in production, less populated area	Economics Public acceptance
	Sealing layers	Poor, discontinuous, faulted and/or breached, unproven	Intermediate and excellent; many pairs, proven	Safety and security of storage
	Trapping mechanisms	Low – relief, absent, unproven	High – relief, proven	Safety and security of storage
	Chemical compatibility	Low	High	Safety and security of storage Reservoir performance Economics
	Site logistics	Poor, far from hydrogen production and/or use, offshore	Good, close to hydrogen production and/or use, onshore or shallow offshore	Economics
	Capacity	Low, not meeting use case	High, meeting use case	Reservoir performance Economics
	Deliverability	Low, not meeting use case	High, meeting use case	Reservoir performance Economics
	Existing infrastructure	Absent, rudimentary, or degraded	Developed and in good condition	Economics Safety and security of storage
	Well density	High	Low to moderate	Safety and security of storage
	Reservoir type	Depleted oil, aquifer, unconventional	Natural gas storage, depleted conventional gas	Safety and security of storage Economics

3.1 Critical criteria

3.1.1 Containment

The fundamental objective of a cyclic hydrogen storage operation is to effectively store and retrieve a required amount of gas. Once injected into the subsurface, gas must be securely contained in the reservoir for subsequent extraction. Therefore, ensuring robust containment in the subsurface is crucial to any cyclic gas storage operation.

At its core, gas containment involves vertical confinement by an impermeable caprock and lateral confinement by an appropriate trapping mechanism.[16] Impermeable caprocks – which may consist of shale, carbonate, or evaporite layers that overlie the porous and permeable storage reservoir – work in conjunction with trapping mechanisms such as geologic structures, like anticlines, or stratigraphic features, like pinch outs.[17] However, the quality of these features varies and their effectiveness can be compromised. For example, impermeable sealing layers may experience hydrogen leakage through fractures, faults (Section 3.2.1), existing wellbores (Section 3.2.11), and pore space (Section 3.1.3). Likewise, faults and fractures, insufficient closure, and shallow relief can reduce the quality of trapping mechanisms (Section 3.2.5). Lastly, site conditions can contribute to undesirable fluid flow patterns like gravity override, which can risk hydrogen trapping or loss. These intricacies are further discussed in subsequent sections.

Several initial indicators provide insights into containment quality. Aquifers, or porous and permeable water-hosting rock, are associated with the greatest uncertainty. Limited or no geological characterization and the absence of naturally occurring gas accumulations contribute to uncertainties about the quality of trapping mechanisms or sealing layers. Conversely, depleted hydrocarbon fields, where subsurface oil or gas accumulations exist, instill some confidence in the presence of an impermeable caprock and trapping mechanism. Nevertheless, slow leaks over geological timescales remain a possibility,[17] indicated by stacked hydrocarbon accumulations and pools that are not filled to the spill point of the trapping mechanism. Lastly, current or recent gas storage sites exhibit promising containment qualities. These sites are proven to contain gas and have demonstrated mechanical stability under injection/extraction cycles and the associated pressure variations.[16] While exhaustive investigations of containment are essential during site development, these indicators serve as valuable screening criteria, offering insights even in the absence of detailed geological characterization.

3.1.2 Potential to affect USDW

Protected groundwater is defined as groundwater with salinity less than a certain threshold, which varies between 4,000 and 10,000 ppm depending on the jurisdiction.[18] The U.S. Environmental Protection Agency defines an underground source of drinking water (USDW) as any groundwater aquifer with a total dissolved solids (TDS) concentration less than 10,000 mg/L.[19]

Subsurface activities such as gas injection for UHS can potentially threaten USDWs. During hydrogen injection, pressure buildup in the formation can drive formation fluids, cushion gas, and injected hydrogen from storage reservoirs, which can migrate into protected aquifers through natural or artificial fluid pathways such as faults or existing wellbores.[18] The leaked gas (e.g., hydrogen, methane) can dissolve into a USDW. Subsequently, fire, explosion, or asphyxiation hazards may occur if the dissolved gas degasses in a confined space (e.g., basement).

Determining whether a USDW has been impacted by gas leaked from a storage facility may be challenging without direct access to monitoring wells or nearby private, domestic water wells. Given the broad and critical impact of the event, rigorous assessment of potential impacts on protected groundwater is essential. With increasing needs for water and reliance on groundwater, sites posing a high risk to water quality should be excluded from consideration.[19] For example, potential storage reservoirs with TDS less than 10,000 mg/L may not be suitable for UHS operations.

3.1.3 Legal accessibility and availability

To conduct subsurface gas storage operations, an operator must have the legal right to use the subsurface pore space. Lack of such rights may expose operators to trespass lawsuits, potential forfeiture of injected gas, or the need to condemn their storage operations.[20]

Global regulations governing legal rights to pore space vary. In some countries, the subsurface is owned entirely by the federal government. In the U.S., subsurface rights are owned by federal or state governments, organizations, or individuals. The U.S. system distinguishes between surface rights and mineral rights, which may be separate or combined for any parcel of land.[21] Mineral rights encompass extractable subsurface resources, including minerals, oil, and gas, while surface rights cover the surface area and structures of the property. Because gas storage does not involve extracting a native mineral resource, which falls clearly into mineral rights, and does not take place entirely on the surface, which falls clearly into surface rights, the required land ownership for gas storage varies in the United States.[20] States such as Michigan and Montana may grant pore space ownership to surface rights owners, whereas in others, like Kentucky, the owner of the mineral rights could own the pore space.[21]

To acquire the legal rights to pore space, land rights can be bought, leased, or acquired by eminent domain from the owner. Some land, such as national parks, protected habitats, and conservation areas, is protected from certain uses or is unlikely to cater to UGS operations (Figure 4). Other land, such as existing or depleted hydrocarbon producing areas, could be easier to acquire or may already exist in an operator's portfolio.

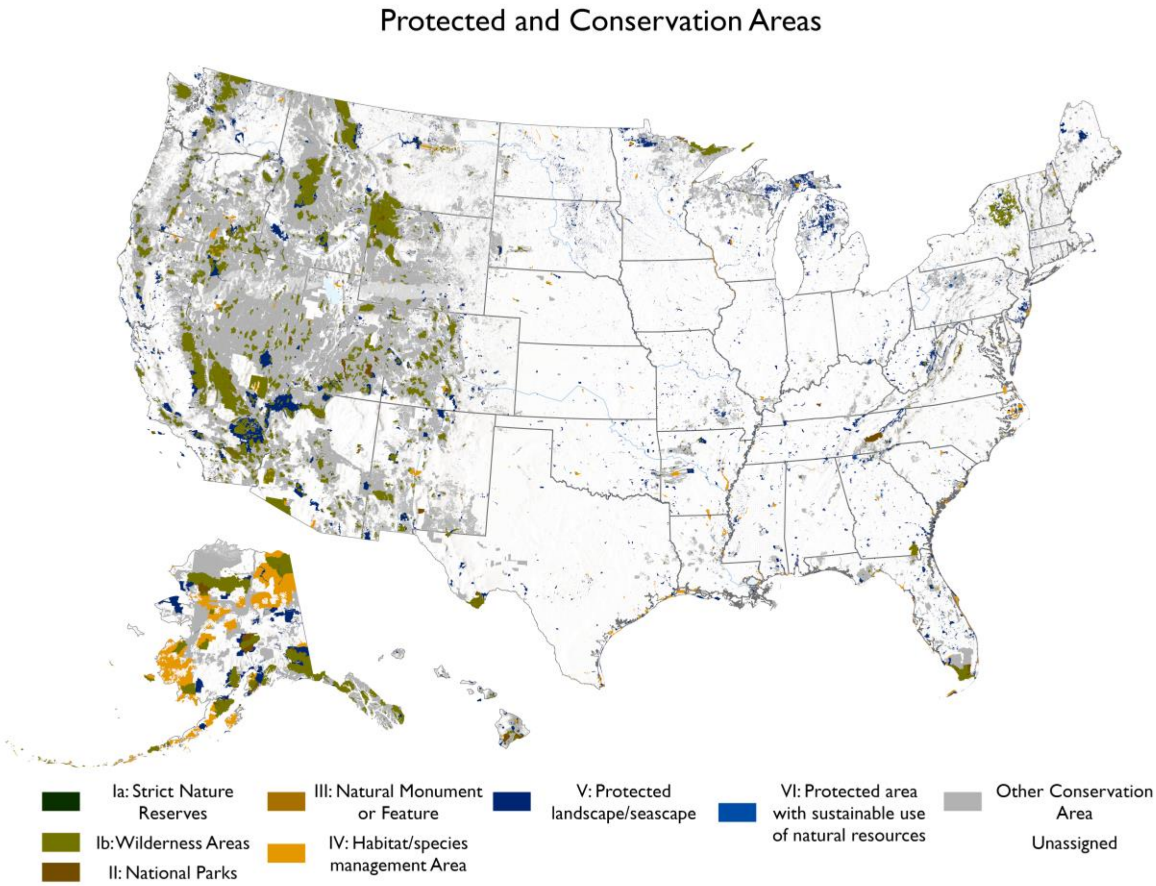

Figure 4. Protected and conservation areas map. Data is from U.S. Geological Survey (USGS) Gap Analysis Project.

3.2 Desirable criteria

3.2.1 Faulting and fracturing intensity

Stressed rocks, commonly found at gas storage depths, often exhibit faults and fractures. Fractures are ruptured surfaces, like a crack, while faults are fractures that show displacement. The nature and severity of faults and fractures within a gas storage system can pose risks of unwanted gas leakage and seismic activity.

Hypocenters of natural seismicity and significant seismic events ($M_{w,}$ >3, where M_w is a measure of an earthquake's magnitude based on its seismic moment) associated with injection activities frequently occur along faults.[22, 23] Also, the presence of faults and fractures within targeted storage sites can create potential pathways for fluid leakage.[23-25] Studies on natural gas storage sites indicate that pressure fluctuations from cyclic gas storage can influence leakage rates through fault zones intersecting storage sites.[26, 27] Such pathways not only lead to the loss of working and cushion gas but also pose the risk of decreased formation pressure, ultimately reducing storage capacity over time. Additionally, gas escaping from subsurface storage sites into shallow formations can trigger chemical reactions, potentially affecting drinking water quality. The properties and internal structures of fault systems can influence fluid leakage by introducing preferential flow pathways. However, characterizing fault zones and fractures is often costly and subject to uncertainty.[28, 29]

Given that the presence of faults and fractures can compromise the integrity of storage systems and introduce uncertainty, and pose risks to storage operations, it is preferable to minimize their intensity for UHS during site screening (Figure 5). While many current natural gas storage sites operate successfully in faulted areas (e.g., California) or use fractures for gas storage space, reducing uncertainty related to faulting in UHS is essential. For hydrogen storage, literature suggests that sites within a 4-km-wide buffer zone around quaternary faults[10] and those with faults extending from the reservoir into the overburden[11] are at higher risk. On a site screening scale, regional geologic and structural maps, along with seismic history, can provide insights into fault intensity. Subsequently, during the site characterization stage, detailed evaluation of intensity becomes essential, especially concerning reservoir boundaries and pressure differentials.

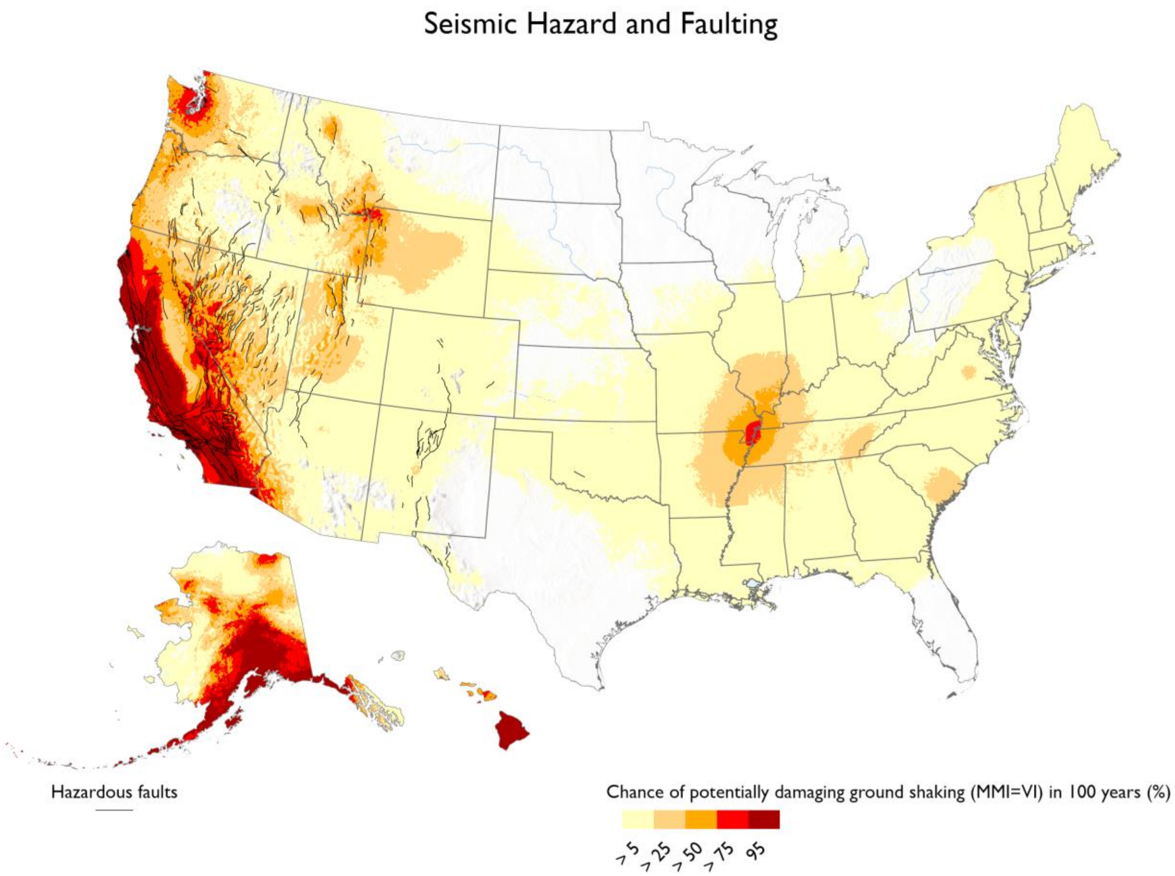

Figure 5. Seizmic hazard and faulting map. Data is from Earthquake Hazards Program, USGS.

3.2.2 Potential for natural or induced seismicity

Closely associated with faulting and fracture intensity, the potential for seismic activity, whether natural or induced, can pose a risk to underground storage systems. Seismicity can alter the mechanical integrity of the storage system, risking gas leakage, or negatively impact stakeholder communities, leading to public opposition to current or future projects.

Natural seismicity is driven by various factors such as fluid flow, stress changes, and more.[30, 31] High seismicity is expected in basins near active margins (i.e., subduction zones), while cratonic basins typically exhibit very low seismicity. Generally, regions in active tectonic regimes are prone to seismicity.[14]

Induced seismicity, on the other hand, is stimulated by pore pressure changes or stress perturbations in the subsurface associated with fracturing processes or injection. Subsurface activities related to oil and gas development,[32, 33] geological CO_2 storage,[34] or geothermal energy production[35] have been attributed to a recent increase in induced seismicity.[36]

Injection/extraction operations for UGS typically have a weak seismic impact.[37, 38] More than 180,000 injection wells exist in the U.S. for both enhanced oil recovery and wastewater disposal. The vast majority of induced seismicity in the U.S. is a result of wastewater disposal.[39, 40] Since gas has higher volume compressibility than liquid, and UHS may not employ wastewater disposal, the impact of hydrogen injection will be less than wastewater disposal. Only a few cases of impactful seismicity potentially related to natural gas storage have been reported for the Gazli gas field (Uzbekistan),[39] Lacq gas field (France),[41] Hutubi UGS field (China),[42] and Castor project (Spain).[43]

However, the consequences should not be underestimated, as negative public perception can lead to project delays or doubts about UHS as a safe technology. For hydrogen storage, literature suggests that sites within a 10-km diameter of seismic events with $M > 5$ and a 5-km diameter of seismic events $M < 5$,[10] as well as sites with high probabilities on the probabilistic seismic hazard index,[8] are at a greater risk (Figure 5). It should be noted that many successful UGS sites are in areas with high seismic hazard. Greenfield sites situated along active margins or brownfield sites correlated with past induced seismicity could pose higher risks for natural or induced seismic events, respectively. Sites with a high likelihood of experiencing damaging seismic activity, as determined through thorough geological and seismic history investigations, should be avoided.

3.2.3 Socioeconomic accessibility and availability

While legal authorization is essential for a UHS operation, gaining social license to operate is equally important. Community support enables a seamless and efficient operation, while a failure to earn it can inhibit the success of gas storage projects. For example, during the initial stages of an onshore gas storage project in the Netherlands, a ban on onshore gas storage was put in place following a public debate.[44]

Community support is responsive to several factors, including a project’s environmental impacts, visual appearance and noise, effect on property values, and broader political implications.[45] Research indicates that the public's acceptance of UGS can vary: 65% of UGS wells are located in urban or suburban land parcels, and 41% have at least one house within 200 meters.[46] Conversely, significant public opposition can arise from incidents like the Aliso Canyon event.[47] Additionally, challenges surrounding a hydrogen storage social license to operate may arise due to unfamiliarity with hydrogen gas and the risks associated its unique chemical and physical properties. Practices that encourage community support throughout a project include thorough risk analysis and transparent communication of the project’s risks, benefits, and broader context to stakeholders.[48]

Communities may vary in their receptiveness to UHS. Communities that have benefitted from past hydrocarbon developments may welcome clean energy developments that use similar skills and infrastructure. Conversely, communities with negative experiences with energy projects in the past, such as natural gas storage leaks, may resist future gas storage initiatives. Further, policy incentives can address socioeconomic factors; for example, the Justice40 program requires that 40% of the benefits of specific federally funded projects be allocated to disadvantaged communities (Figure 6).

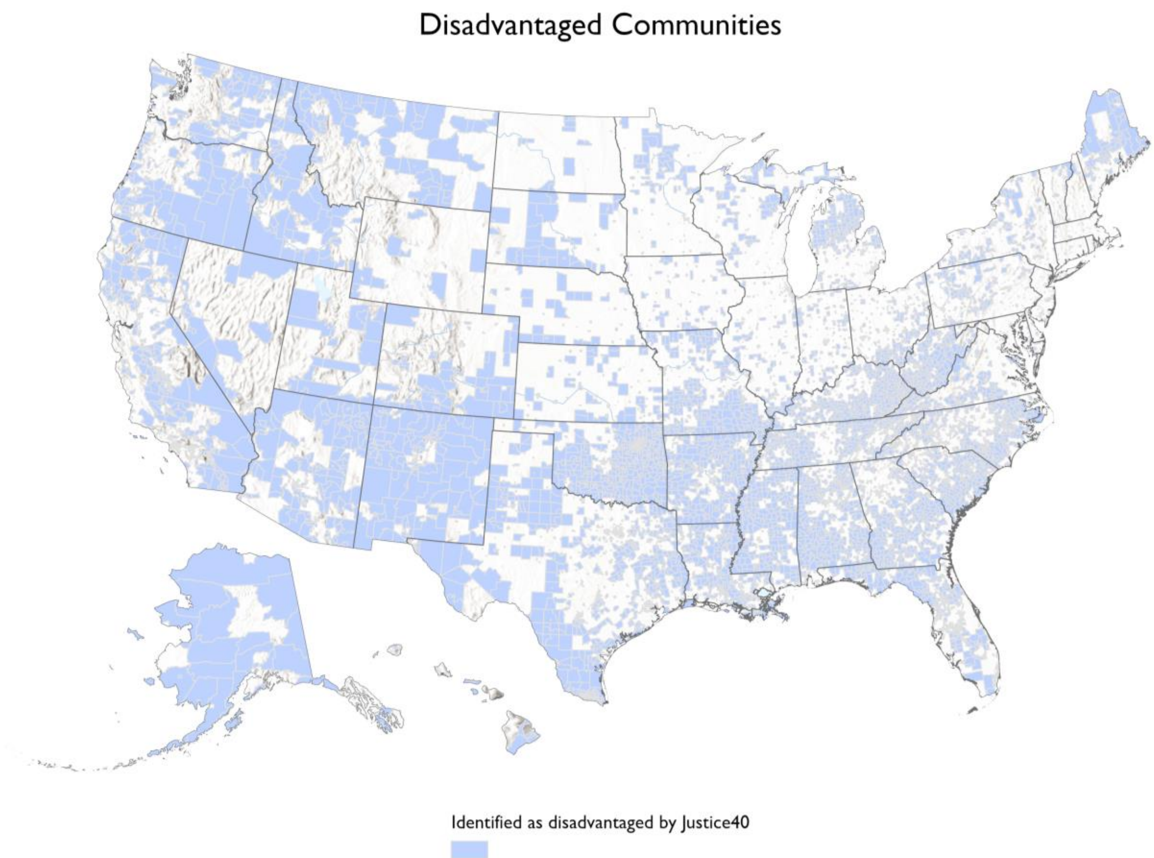

Figure 6. Disadvantaged communities as defined by the U.S. Department of Transportation's Climate and Economic Justice Screening Tool (CEJST). This tool identifies overburdened and underserved census tracts by using eight metrics: climate change, energy, health, housing, legacy pollution, transportation, water and wastewater, and workforce development.

3.2.4 Sealing layers

Gas stored in the subsurface naturally seeks to rise due to its lower density compared to surrounding fluids. Preventing gas from escaping the subsurface requires an overlying impermeable flow barrier, typically composed of mudstone, carbonate, or salt rock layers. Therefore, the presence of at least one sealing layer is a fundamental requirement for gas storage.

Gas can potentially escape a sealing layer through pore media, fractures, or by diffusion through porewater.[16] Hydrogen, specifically, possesses unique physical properties such as low density, low viscosity, and high diffusivity relative to other gases, which may increase the risk and speed of its escape. However, its low solubility in water might mitigate these risks.[49] Whether hydrogen is more susceptible to leaking through the pore space of a caprock than natural gas is an area of active research.[50, 51] Additionally, dissolution and diffusion losses of hydrogen are expected to be small (< 0.1% to 2.2% of stored hydrogen) and decrease with each injection/extraction cycle.[45, 52] Regardless, escape through leaky pathways like fractures that penetrate through the caprock poses a risk of rapid hydrogen leakage. A high-quality sealing layer is integral to effective gas storage.

Sealing layer quality is primarily determined by permeability, thickness, and continuity. Lower permeability ensures that hydrogen cannot escape through the caprock. Although ideal permeabilities for caprocks are not extensively documented, suggested minimum reservoir values are as low as 0.1 mD,[53] indicating that the caprock should have permeability below this threshold. Additionally, thickness improves the geomechanical strength of a caprock, reducing fracture likelihood and the potential for faults or fractures to provide escape routes for stored gas. Minimum caprock thicknesses recommended in the literature range from 10 to 50 meters.[7, 8, 10, 54] While multiple layers may help prevent leakage to the surface, the immediate sealing layer is the most important in retaining stored gas within the reservoir. Lastly, the continuity of the permeability and thickness across the reservoir formation also needs to be accounted for. A discontinuous caprock, such as a silt lens in a deltaic environment, could risk gas migration around it.

3.2.5 Trapping mechanisms

The primary function of a trap is to maintain a compact, extractable gas cap. Sealing layers prevent vertical fluid migration, while trapping mechanisms constrain lateral fluid movement.[16] Understanding trapping mechanisms is important for assessing extractability, recovery potential, and storage capacity.

Trapping mechanisms can arise through various stratigraphic or structural elements. Stratigraphic features like pinch outs or unconformities, as well as structural elements such as anticlines or faults, can act as trapping mechanisms.[17] The quality of trapping mechanisms, influenced by factors like type, closure, and relief, significantly impacts gas plume containment and the available pore volume for gas storage.

The type of trapping mechanism can affect the security of a hydrogen plume. For instance, fault-bound trapping structures may increase risks of hydrogen loss due to exposure to reactive minerals or enhanced fluid flow pathways for hydrogen escape.[44] The relief of a trapping structure also impacts plume development. Studies indicate that steeply dipping or high-relief trapping structures are advantageous for improving hydrogen recovery and decreasing complicated, buoyancy-driven fluid flow patterns.[55, 56] Recent research suggests that a reservoir dip of 5 to 10 degrees is optimal for maximizing hydrogen productivity.[10] The closure of the trap is a critical factor that determines the reservoir's hydrogen storage capacity. An optimal closure allows for sufficient hydrogen storage; some industry experts suggest that closures less than 20 meters may be less effective for gas storage.[57]

On a site screening scale, trap quality could be informed by analyzing the depositional environments of the storage system, regional structure maps showing anticlines and faults, geologic cross sections showing unconformities and pinch outs, or existing hydrocarbon field data on trapping mechanisms.

3.2.6 Chemical compatibility

The compatibility of underground storage systems with hydrogen is important, as geochemical and microbial reactions can affect the integrity and efficiency of hydrogen storage. Hydrogen may react with CO_2, SO_4^{2-}, CO_3^{2-}, Fe^{3+}, and others that can lead to the formation of undesirable by-products like CH_4, HS^-, CH_3COO^-, Fe^{2+}, and/or others. These reactions, which can occur by abiotic processes and/or be catalyzed and accelerated by hydrogenotrophic bacteria,[58] may result in hydrogen consumption, mineral dissolution/precipitation, and biofilm formation, which can impact storage capacity, extractability, and injectivity.

The risk associated with biogeochemical reactions remains somewhat uncertain but potentially significant. While studies focusing solely on abiotic reactions in sandstones suggest minimal hydrogen losses under storage conditions,[58, 59] experimental investigations involving calcite-rich rocks have shown substantial reduction (i.e., a greater than 40%) in porosity due to hydrogen–calcite reactions (e.g., Al-

Yaseri et al.[60]). When microbial activity is considered, simulation studies show relatively small (i.e., 0.01% to 3.7% of stored hydrogen) gas consumption,[52, 61] yet experimental studies report microbial processes could consume as much as ~32% to 40% of the stored hydrogen.[62, 63] Field observations also support these findings, with microbial activity leading to notable hydrogen consumption (i.e., ~17%) in some cases, such as in Lobodice, Czechia.[61] Ongoing work aims to identify key storage properties influencing biogeochemical interactions to mitigate these effects.

Minerology, water chemistry, and storage conditions may influence biogeochemical reactions during hydrogen storage. Studies agree that promising reservoir minerology for hydrogen storage typically consists of abundant quartz and minimal carbonate, sulfur, and clay-bearing minerals[9, 63-65] Concerning fluid chemistry, low carbon, sulfur, and iron-content in connate gas and water are preferable.[65] Specifically, one simulation study suggests that SO_4^{2-} concentration less than 1,250 mg/L may result in minimal hydrogen losses over 1 year.[66] Further, reservoirs with high salinities (4.4 M NaCl, equivalent to at least 262,550 ppm TDS), pH values outside the range of 6 to 8, and low or no oil saturation may limit the growth of hydrogenetrophic bacteria.[9] For reference, most water chemistry of hydrocarbon reservoir rocks in the U.S. exhibits ~ 100 to 1,000 mg/L SO_4^{2-} and HCO_3, 6 to 8 pH, and 10,000 to 200,000 mg/l TDS (Figure 7, top). Additionally, potential reservoir rocks (defined as sandstone, siltstone, and carbonate rocks) mostly fall between 10% to 85% quartz, 0% to 35% calcium oxide (which forms from exhumed carbonate minerals), and less than 1% sulfate and sulfide minerals (Figure 7, bottom). Of course, sandstone reservoirs will fall on the higher end of the quartz spectrum and the lower end of the calcium oxide spectrum, whereas the reverse is true for carbonate reservoirs.

Additionally, storage conditions such as temperature play a crucial role in determining the risk of biogeochemical reactions. Broadly, higher temperatures may discourage the growth of hydrogenetrophic bacteria. For example: No known hydrogenetrophic bacteria can grow at temperatures greater than 122°C. Lower temperatures (> 75°C), together with high salinities (1.4 M NaCl, equivalent to at least 81,682 ppm TDS), can also limit hydrogenetrophic bacteria growth.[61] However, there is a complex interplay of storage conditions on biogeochemical processes. For example, higher temperatures (> 90°C) may increase the speed of abiotic reactions,[59] and higher salinity can increase the risk of salt precipitation around the wellbore, which could limit gas storage efficiency.[64] For reference, most natural gas storage sites in the U.S. report temperatures around 40°C, with few exceeding 90°C (Figure 8c). Additional research is required to determine which of the two processes is more important for hydrogen storage security.

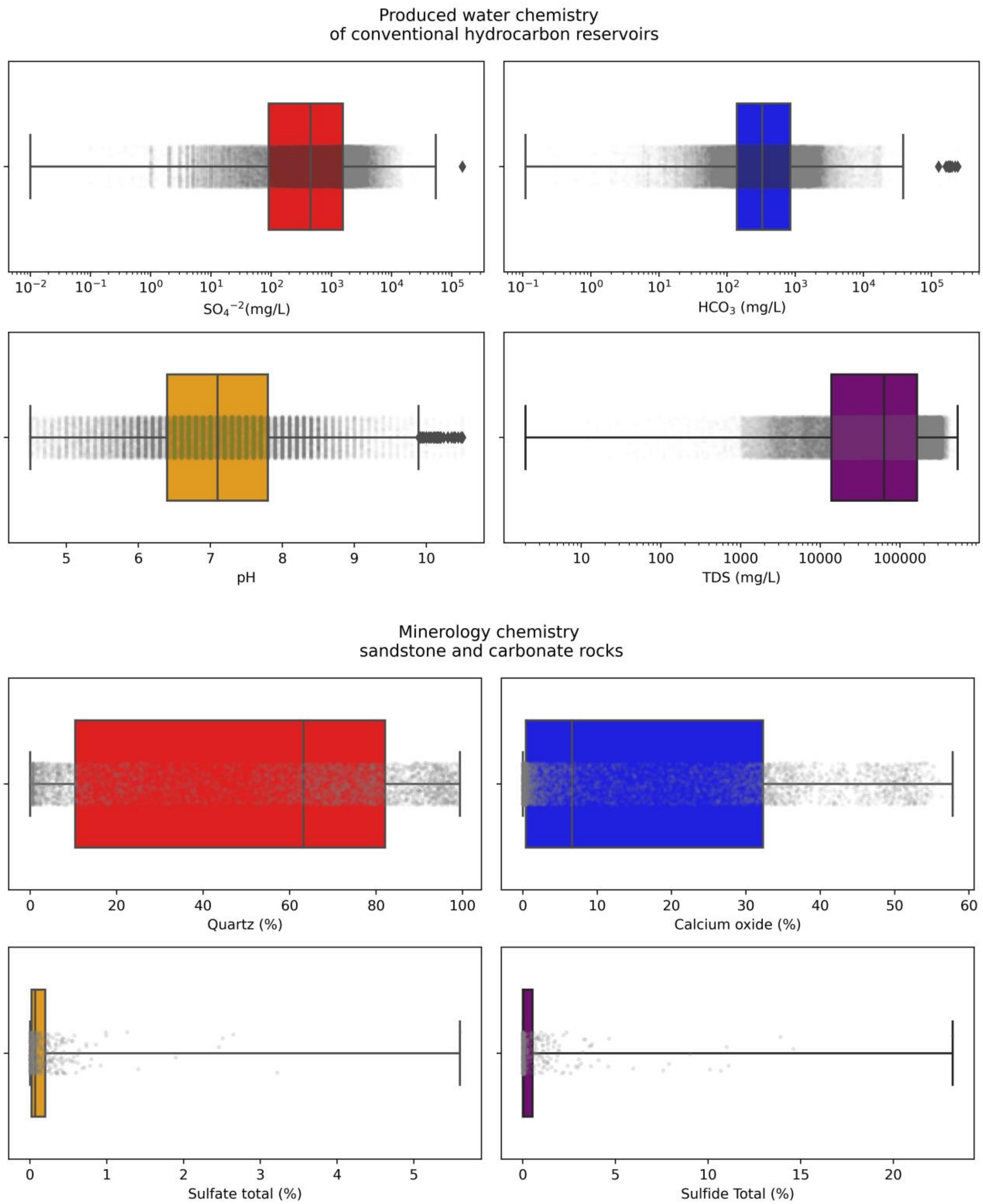

Figure 7. Produced water and rock chemistry data from various hydrocarbon reservoir rock types in the U.S. The ions and minerals are shown based on two criteria: (1) their data completeness in the dataset, and (2) their potential influence on the success of hydrogen storage in the subsurface. Data from USGS National Produced Waters Geochemical Database (3.0) and USGS geochemistry of rock samples from the National Geochemical Database.

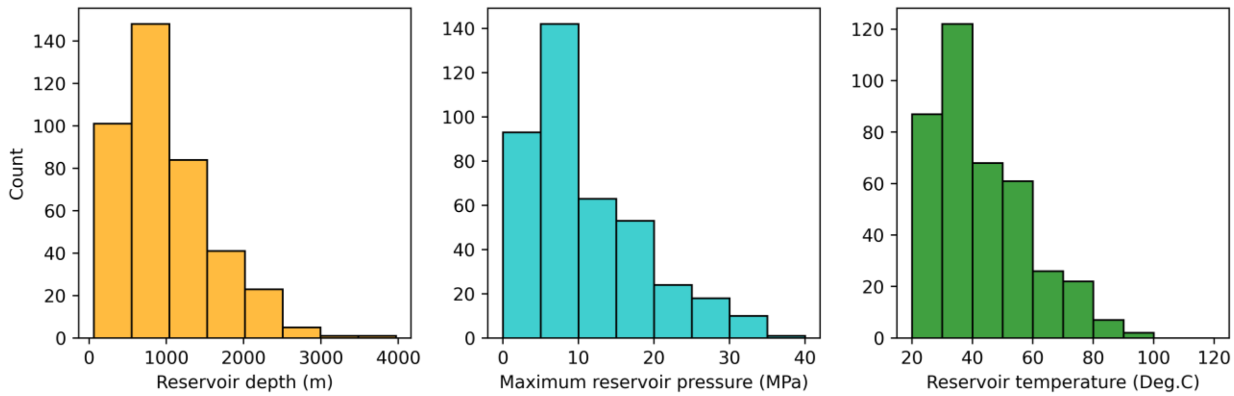

Figure 8. Reservoir properties of existing underground natural gas storage sites that could impact underground hydrogen storage. Data is from the Pipeline and Hazardous Materials Safety Administration and the U.S. Energy Information Administration.

3.2.7 Storage capacity

The goal of cyclic gas storage is to store and deliver a required volume of gas to end users. Thus, a basic and important requirement for UHS is sufficient storage capacity – defined as the maximum volume of gas that can be stored in an underground storage facility in accordance with its design, including the physical characteristics of the reservoir, installed equipment, and site-specific operating procedures.[67]

Estimating the capacity of a storage site is an iterative process that is highly dependent on data availability. In porous rock formations, gas occupies the available pore volume. The amount of gas that can be stored is constrained by myriad factors, including geomechanical (e.g., fracture pressure), hydrodynamic (e.g., capillary entry pressure), structural (e.g., trap closure), and operational (e.g., injectability/extractability) considerations. As understanding of these constraining factors improves, so does the confidence in the capacity estimates.[68] Capacity estimations fall into two categories: (1) static, which calculates the gas volume the reservoir can hold based on static components, and (2) dynamic, which considers injection and extraction constraints over a certain period.[16] Generally, static capacity estimations are useful early in the site quality assessment process, whereas dynamic estimations become more relevant as more data becomes available.

Several methods exist for estimating capacities on a regional scale. Basic geometric volume calculations are often used for porous formations[69] utilizing data such as areal extent, depth, thickness, and porosity to estimate available pore space. However, these estimates may overlook critical factors such as trap closure, which is critical for cyclic gas storage. For depleted or existing hydrocarbon fields, capacity estimation involves assuming that pore space previously occupied by hydrocarbons or water is now available for gas storage.[68] This approach inherently incorporates trap closure. Similarly, for natural gas storage sites, pore space used for natural gas storage is assumed to be available for other gas storage.[53] This method is effective because in addition to trap closure, the historical gas storage capacity inherently accounts for geomechanical, hydrodynamic, structural, and operational constraints. Lastly, more detailed, site-specific capacity estimates consider dynamic constraints such as deliverability and recoverability based on comprehensive, site-specific data.[52, 56, 70] Eventually, capacity estimates must be holistic and integrated across various data sources to confirm a reservoir's ability to store the required amount of gas for end users.

The optimal capacity for hydrogen storage depends on its specific use cases across various sectors like power generation, transportation, heating, and industry. Existing hydrogen storage facilities used by industry store between 0.028 TWh (= 9.86 MMm^3 = 0.83 MMkg) and 0.12 TWh (= 44.2 MMm^3 = 3.72 MMkg) of hydrogen in salt domes.[5] For the electricity and heating sectors, natural gas storage sites serve as a relevant benchmark. These sites have total maximum capacities between 1 million and 10 billion m^3 natural gas (Figure 9), which can equate to between 0.0014 TWh (= 0.5 MMm^3 = 0.042 MMkg) and 12.79 TWh (= 4563.17 MMm^3 = 384 MMkg) of hydrogen working gas (Figure 10).[53]

While smaller reservoir capacities do not necessarily indicate poor suitability for UHS, as demonstrated by the effectiveness of salt caverns in maintaining peak-time gas reserves,[5] higher storage volumes are generally preferred due to economies of scale.[71] Nonetheless, the minimum required hydrogen storage capacity will be defined by the specific use cases and needs within each sector.

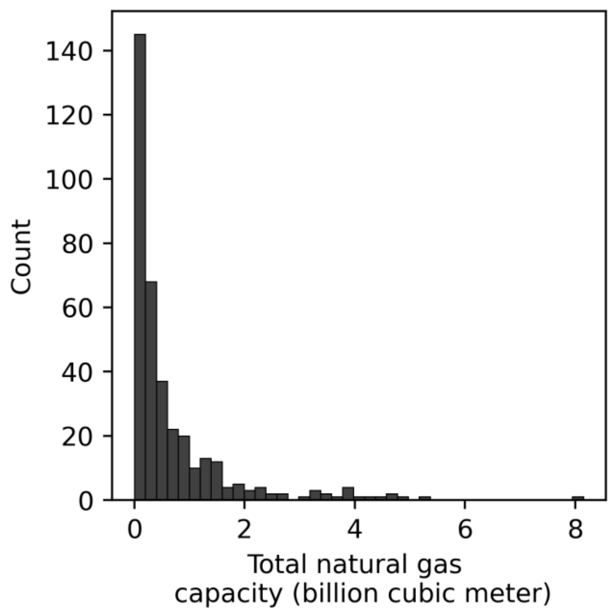

Figure 9. Reported capacities for natural gas of existing natural gas storage sites. Data from the U.S. Energy Information Administration.

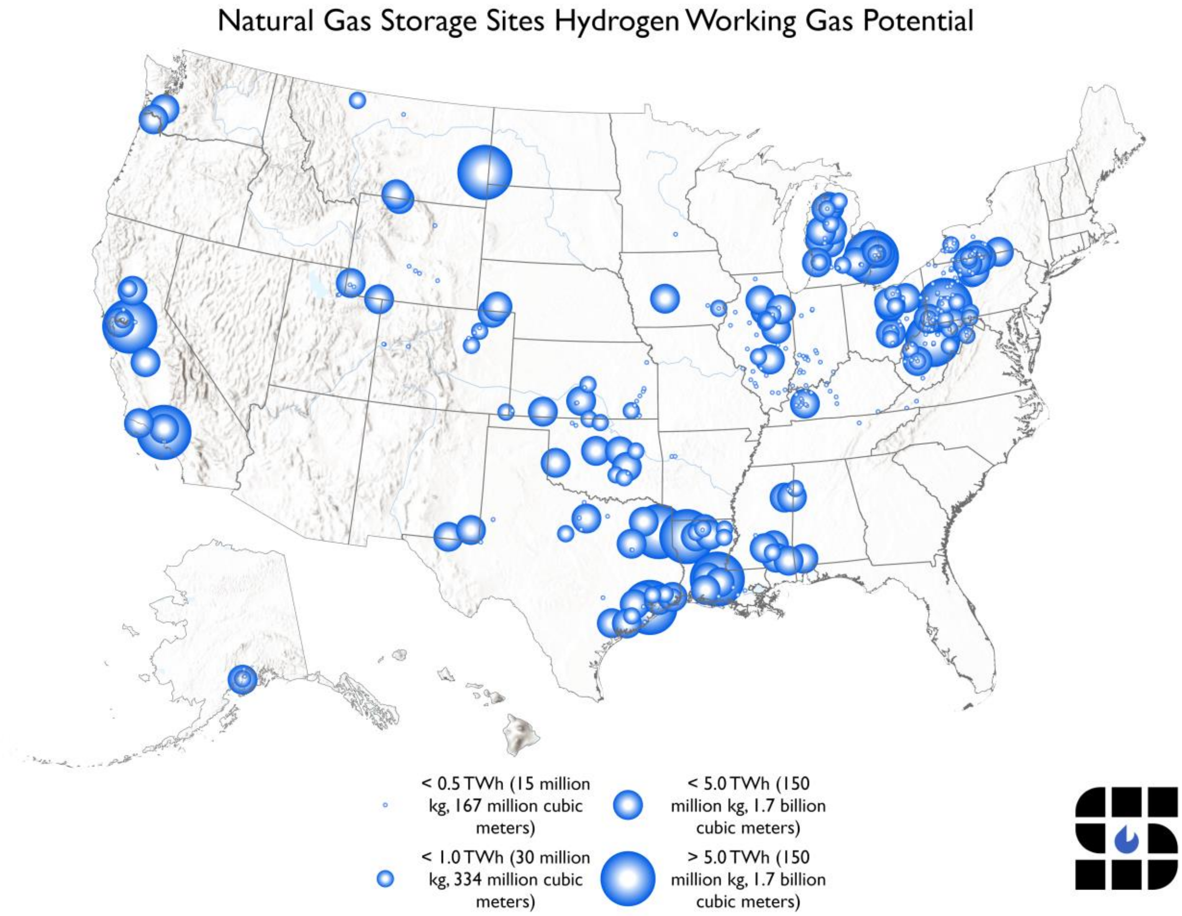

Figure 10. Calculated hydrogen working gas potential offered by existing underground natural gas storage sites.[53] Gas volumes are given at standard conditions.

3.2.8 Deliverability

Deliverability – defined as the amount of gas that can be withdrawn from a storage reservoir over a 24-hour period[67] – determines if a gas storage operation can provide the required amount of hydrogen to a given use case.

Deliverability hinges on several factors, including the current gas volume in the reservoir, permeability of the reservoir rock, reservoir pressure, compression capabilities, and the configuration of associated surface facilities.[23] Reservoir deliverability within a gas storage site is often regarded as a design parameter, with well infrastructure design significantly influencing this aspect.[72] The deliverability rate of a facility directly correlates with the total gas volume in the reservoir. It reaches its peak when the reservoir is at maximum capacity and gradually diminishes as working gas is withdrawn.

On a site screening scale, the assessment of deliverability can be guided by historical hydrocarbon production rates (for hydrocarbon reservoirs), historical gas deliverability (for gas storage sites), and/or reservoir formation permeability (for aquifer sites). Existing natural gas storage facilities typically exhibit maximum deliverabilities between 0.0001 and 0.1 billion m^3 of natural gas per day (Figure 11). The literature suggests lower permeability ranges for gas storage reservoirs varying from 50 to 0.1 mD.[10, 53]

Facilities with higher deliverability characteristics at a given pressure drop are preferred due to their enhanced flexibility in meeting fluctuating hydrogen demands. While lower deliverability may not be inherently unfavorable, as it can align with specific use cases, it may present challenges during periods of peak demand, impacting the continuous supply of hydrogen.

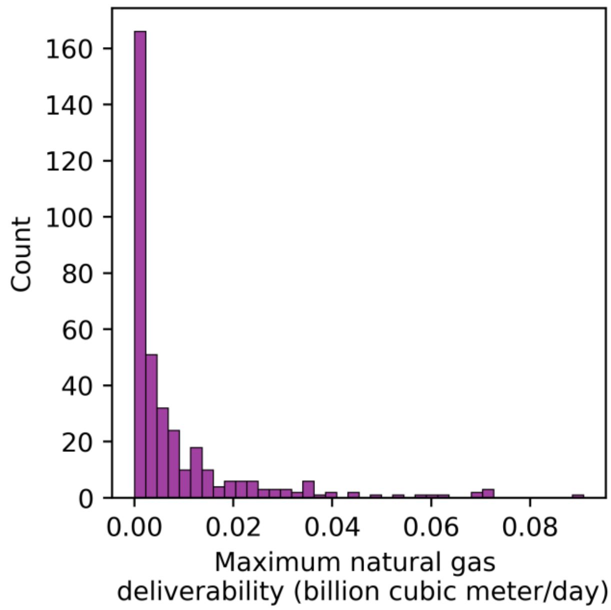

Figure 11. Reported deliverabilities for existing natural gas storage sites. Data from the U.S. Energy Information Adminstration.[67]

3.2.9 Reservoir type

Reservoir type is a critical factor in the site screening and selection process for UHS, providing essential information on containment capabilities, trapping mechanisms, sealing layers, and existing infrastructure. Natural gas storage reservoirs, depleted gas and oil reservoirs, and saline aquifers are among the natural porous media considered for UHS sites (Figure 12 and Figure 13).

In the realm of porous media reservoirs, natural gas storage reservoirs and depleted gas reservoirs stand out as prime candidates for potential hydrogen storage sites.[1, 68] Several factors contribute to this preference:

- Existing infrastructure: These reservoirs have established infrastructure, including wells, surface facilities, and pipelines. The presence of these facilities can significantly reduce both the time and cost associated with storage operations when compared to developing entirely new facilities.
- Large pore space volume: Gas reservoirs, in particular, offer substantial storage capacity due to their larger size and higher recovery factor.
- Proven containment characteristics: Years of natural gas storage operations have demonstrated that these reservoirs provide reliable containment.

Features such as caprock sealing and lateral closure have been validated through the accumulation and storage of hydrocarbon gas.[1] Depleted gas reservoirs, while sharing similarities with natural gas storage reservoirs, differ in that they have not undergone repeated gas storage and withdrawal operations. While residual gas in the reservoir can act as cushion gas to maintain the required reservoir pressure,[1] the composition of the naturally occurring hydrocarbon residue is uncertain and may impact the purity of the gas stream produced. As such, extra equipment, processes, and energy are required to remove these from the hydrogen. Although these effects diminish over time due to the limited concentration of impurities, it is important to consider them in the site selection stage.[1]

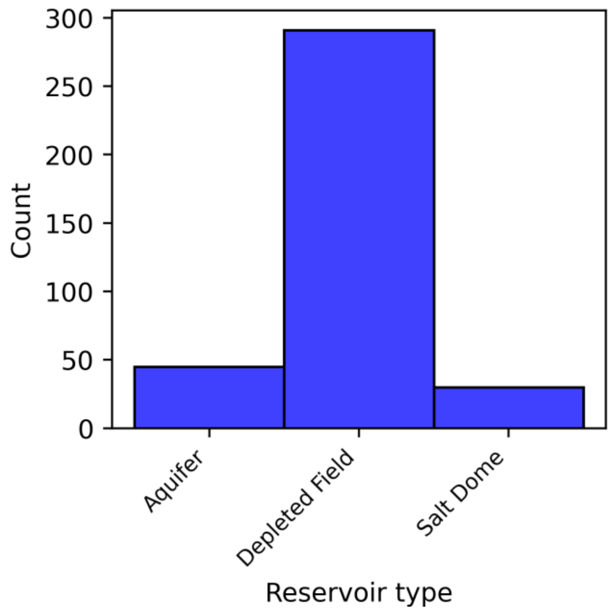

Figure 12. Reported reservoir types of existing natural gas storage sites. Data is from the U.S. Energy Information Administration.

Conversely, depleted oil reservoirs and aquifers are comparatively less favored.[1, 5, 68] Oil reservoirs typically have smaller size and lower recovery factors than gas reservoirs, limiting their storage capacity. Additionally, the dissolution of injected hydrogen in the oil phase presents challenges, increasing possibility of chemical reactions and conversion of hydrogen into, e.g., methane and consequently introducing complexities in inventory estimations.[1] Potential issues, such as liquids in the wellbore, gas enrichment, and condensate formation in pipelines, further complicate the storage process. However, the production of oil in surface facilities could increase gas storage capacity while the gas enrichment could increase the heating value of the produced gas. However, this would also increase carbon emissions upon combustion.

Aquifers, on the other hand, are in an immature stage of development among porous rock reservoirs. In contrast to the depleted oil and gas deposits, a comprehensive preliminary evaluation is necessary for aquifer storage systems, requiring the establishment of new infrastructure. Special attention is required for caprock integrity and trap closure, a critical factor for ensuring both safety and resource containment.[73] Therefore, aquifers require the drilling of wells for detailed, laborious, and costly tests to determine the tightness of the entire storage site. This makes the creation of such a storage facility more expensive and less certain, and is reflected in the reservoir types used for existing natural gas storage sites (Figure 13).[5] Aquifers could also require more cushion gas and allow less flexibility in injection and withdrawal cycles. Bai et al.[74] reported that under the same conditions, the required cushion gas volume for storage of hydrogen in a depleted oil and gas reservoir is 33%, while 33% to 66% is required in an aquifer.

Despite these challenges, aquifers exhibit several favorable characteristics. Aquifers are common in sedimentary basins globally,[1] providing higher accessibility compared to hydrocarbon reservoirs. Thus, they may present an alternative for UHS in those areas where depleted hydrocarbon deposits or salt caverns are not available. Many of them are situated close to major energy consumers or large cities. Additionally, they have been safely used as natural gas storage sites for decades (e.g., Midwestern United States, Figure 13),[5] and the required new infrastructure can be tailored for hydrogen storage, offering increased system efficiency and safety. Moreover, the presence of fewer legacy wells than in depleted hydrocarbon fields is advantageous, limiting risks of resource loss and environmental contamination.

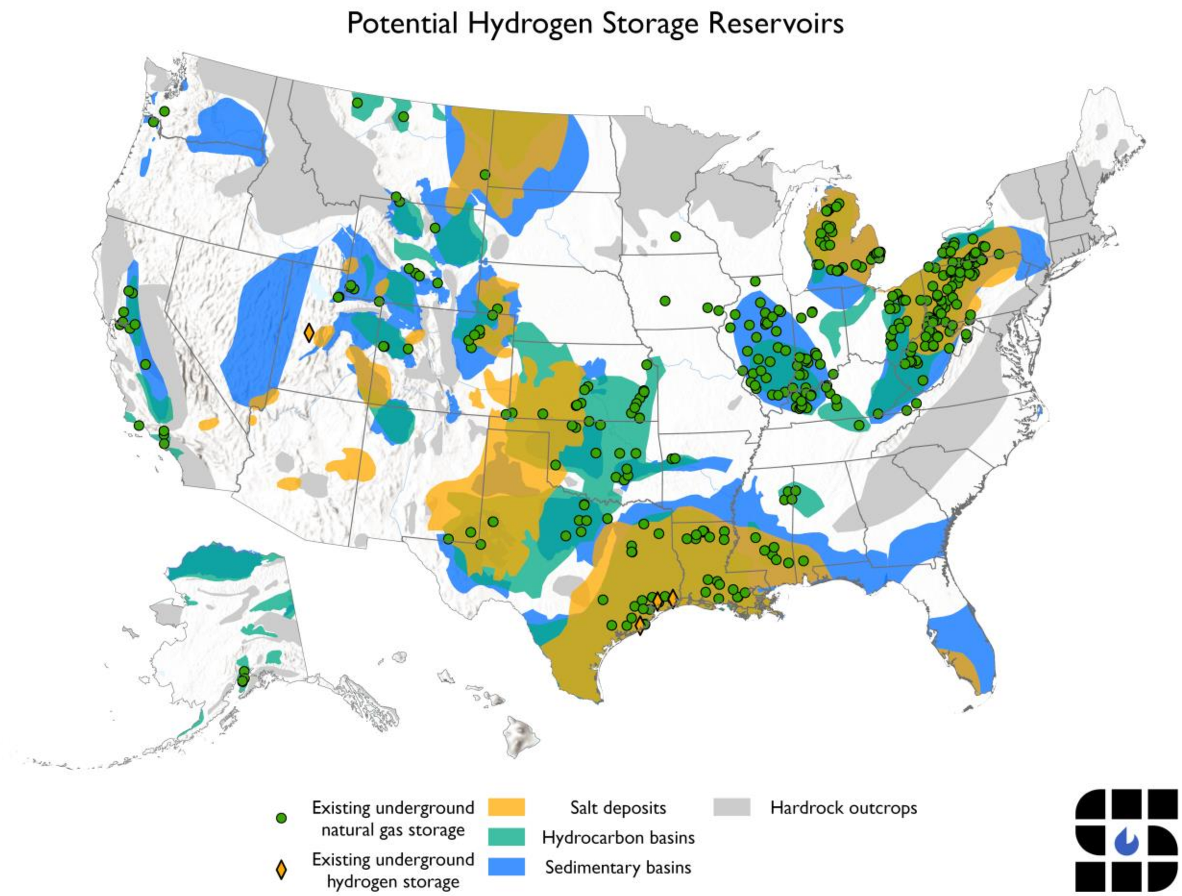

Figure 13. Potential storage reservoirs for underground hydrogen storage. Data is from Hibbard et al.[75]

3.2.10 Existing infrastructure

The readiness of infrastructure plays a pivotal role in determining the feasibility and efficiency of early-stage development for UHS sites. Infrastructure, particularly in fields such as natural gas storage reservoirs or depleted oil and gas reservoirs, can significantly impact the initial capital investment and time required for development.

Sites with pre-existing infrastructure, including surface facilities such as compressors, separators, and pipeline connections, as well as subsurface facilities like wells and sensors, may offer substantial cost savings (Figure 12). These sites often require reconditioning and repurposing rather than the extensive development needed for undiscovered or less-equipped locations with no operational history. Sites with existing infrastructure have likely undergone previous characterization efforts that could reduce the need for extensive data acquisition processes such as seismic studies, wireline logging, or exploratory drilling, depending on data quality. This not only could minimize development costs but could also result in relatively lower uncertainty regarding resource containment, as these sites have been proven through past operations or hydrocarbon accumulations. Regions with established infrastructure also tend to offer additional advantages, including access to relevant businesses such as utility suppliers and availability of experienced labor. However, the condition of pre-existing infrastructure will determine the degree of cost savings achieved.

Given this evidence, regions with existing infrastructure and established industrial maturity emerge as preferable choices for successful UHS projects. For example, depleted natural gas or oil reservoirs and existing or inactive natural gas storage sites could be preferable over greenfield aquifer storage sites. However, depleted gas and oil reservoirs may feature many historical wells that require proper plugging to prevent negative impacts. When using existing infrastructure, storage operators can focus less on site design and construction but must pay more attention to converting and maintaining existing infrastructure, ensuring compliance with safety guidelines, and meeting expected performance metrics, such as storage capacity and deliverability for UHS operations.

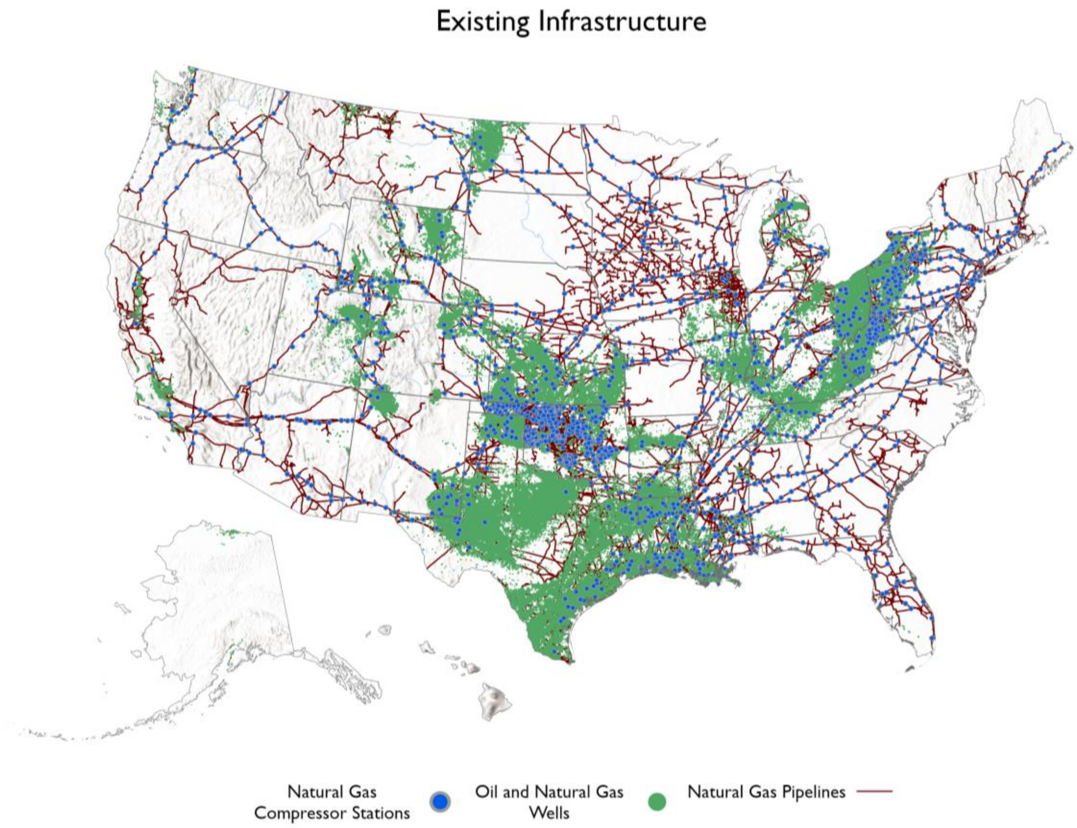

Figure 14. Existing gas infrastructure that could contribute to underground hydrogen storage. Data is from the Homeland Infrastructure Foundation-Level Data (HIFLD) Database (HIFLD Natural Gas Compressor Stations; HIFLD Oil and Natural Gas Wells; HIFLD Natural Gas Pipelines)

3.2.11 Well density

Wells that penetrate a gas storage system can provide valuable geologic data and existing avenues for injecting and extracting gas but can also serve as a leakage pathway for injected fluids. Thus, the density of wells at a storage site impacts data quality, economics, and storage security.

Well leakage can occur through the casing-cement-rock annular system, such as residual drilling fluid creating specific pathways, gas channels formed during primary cementing, and micro-annuli generated by pressure and temperature fluctuations.[76] Larger well leakage events can also occur if well materials fail completely.[77] Annular over-pressurization is often attributed to the wellbore leakage into USDW. Well blowout events are also a concern for UGS facilities. In 2015, the SS-25 well at the Aliso Canyon Storage Facility outside of Los Angeles failed and released ~ 0.1 million metric tons of methane into the atmosphere.[47] A root cause analysis revealed that the lack of an additional redundant barrier in the well led to the catastrophic event. Analyses of well construction data have shown that more than 11,000 wells at existing UNGS facilities in the U.S. have a single-point-of-failure design similar to the SS-25 well at the Aliso Canyon Facility. This design is characteristic of older wells that were not originally installed for UNGS.[77] Additionally, if sites are not perfectly isolated, pressure changes by operations in proximal subsurface gas storage sites can interfere with one another. The injected fluids could also migrate, interacting with more abandoned wells and increasing the risk of resource loss, contamination in overlying aquifers, and the subsequent costs of remedial actions.[68] Therefore, a lower density of pre-existing wells is preferred for UHS.

On a site screening scale, several lines of evidence contribute to assessing the risk associated with well density. Firstly, public well databases like the Homeland Infrastructure Foundation Level Database (HIFLD) oil and gas well database offer direct insights into well density within a potential storage area (Figure 12). Secondly, the history of the potential storage sites, distinguishing between brownfield and greenfield sites, can provide valuable information on risks related to wells. Brownfield sites typically have existing wells whereas greenfield sites do not. Lastly, the nature of a brownfield site can influence well risk. In brownfield sites, areas with stacked hydrocarbon accumulations, compared to non-stacked pools, may have more wells penetrating each storage reservoir, potentially creating pathways for leakage. Additionally, older brownfield sites may have older wells compared to newer brownfield sites with updated well infrastructure.

3.2.12 Site logistics

Site logistics encompasses a storage site's proximity to both end users and hydrogen production, proximity to transportation corridors, proximity to usable infrastructure, terrain accessibility, and other factors. These are important considerations because they impact the technical and economic viability of hydrogen storage and transport.

On a site screening scale, logistical considerations can inform technical and economic suitability. A study by DeSantis et al.[78] highlighted that electrical transmission costs are greater than costs associated with hydrogen transportation through pipelines, suggesting an economic advantage in situating UHS facilities closer to hydrogen production sources (if electricity is used to produce hydrogen). Given that pipelines represent the most efficient method for transporting large volumes of hydrogen gas, leveraging an existing pipeline network – provided the materials are compatible with hydrogen – can significantly enhance the viability of a project. Additionally, obvious terrain differences, such as offshore vs. onshore locations, may have significant implications for the technical feasibility and economic viability of a project. For example, transporting equipment, personnel, and supplies is less challenging at an onshore location. Additionally, deepwater drilling demands advanced technologies to reach reservoirs buried deep beneath the seabed. Conversely, onshore storage sites can present their own logistical challenges, such as seeking community and legal permissions that may be absent offshore.

Determining the optimal logistics for a UHS project requires a comprehensive analysis that goes beyond mere proximity, transport mode, and terrain accessibility. It necessitates a careful evaluation of the trade-offs between new infrastructure investments and the dynamics of supply and demand. To accurately assess these factors, a detailed techno-economic analysis is essential (see Misra et al.[71]). Such an analysis should consider not only the immediate logistical and economic benefits but also the long-term sustainability and efficiency of the storage and transportation infrastructure.

4.0 Application

Understanding the key considerations for UHS is the first step in the process of identifying a suitable storage site. The site screening criteria presented above are shaped by industry expertise and primary research, highlighting factors that could significantly impact UHS. With this knowledge, stakeholders interested in hydrogen storage can collect pertinent data for their specific study region.

Next, this collected data needs to be used to pinpoint favorable sites for hydrogen storage. Ideally, the selection process will prioritize criteria based on their importance, starting with those that have the most influence on the success of a hydrogen storage operation and then progressively refining the selection based on less impactful criteria. However, challenges arise in this approach due to varying data completeness across sites and regions, coupled with uncertainties regarding the relative importance of criteria because of the relative immaturity of research and field experience surrounding UHS. Therefore, a criterion-by-criterion comparison, ordered by importance, is not feasible. The next best approach is to generate a holistic, comparative methodology that uses all (or most) of the data available to reduce uncertainty surrounding the potential site's effectiveness for hydrogen storage.

Therefore, we propose a methodology as follows:

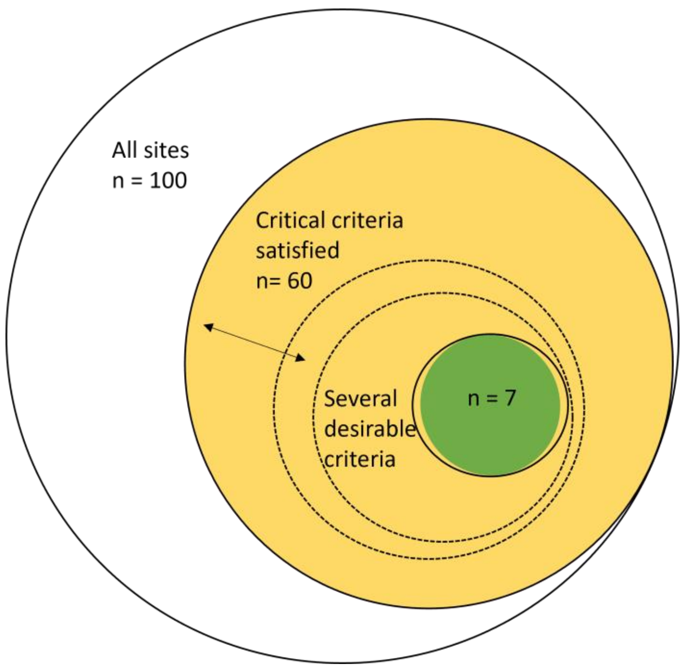

Figure 15. Site screening methodology. The dotted lines and arrow represent the ability to elevate some desirable criteria to critical based on quantity of potential sites, region-specific factors, and data accessibility. The values are arbitrary and are for example only.

1. Compile all relevant public and available data for the study region. The result is a comprehensive database of potential sites and their associated information.
2. Identify factors that could render a hydrogen storage project unfeasible or exceptionally challenging, such as legal constraints or signs of gas containment issues, resulting in a selection of potential sites where hydrogen storage could potentially succeed (Figure 15, critical criteria). Ambiguity surrounds these factors, leading to potential shifts in criteria classification from desirable to critical. This reclassification can be influenced by the quantity of potential sites,

region-specific factors, and data accessibility (as denoted by the dashed line in Figure 15). For instance, if no sites meet the critical criteria, stakeholders may opt to explore a different study region. Conversely, if numerous sites meet the critical criteria, stakeholders may elevate certain desirable criteria to critical status.

3. Evaluate factors that could influence the project’s success, including physical and chemical properties, existing infrastructure, historical performance, and logistical aspects. The result is the identification of potential sites that show more positive indicators for hydrogen storage (green in Figure 15) than their counterparts. The number of potential sites to select depends on how many sites the stakeholder can collect new data for in the next stage of site selection: site characterization.

The benefit of this methodology is its flexibility. Each case can define a set of critical and desirable criteria based on data availability, regional considerations, and the state of research. The criteria presented here are a product of the current state of research and field experience and thus are subject to change over time as research advances and field experience grows.

5.0 Conclusions

In this report, we have compiled a comprehensive set of criteria for site screening in the selection process for UHS and provided benchmarks for these criteria, when data allows, to aid future stakeholders. The site screening process leverages existing data and public information to streamline the identification of potential storage sites from numerous candidates to a more manageable number. Our proposed methodology encompasses critical and desirable criteria, detailing 15 specific factors (Table 1) aimed at refining the selection of UHS sites and qualitatively assessing their suitability.

Each criterion has been developed based on insights from literature on site selection for UNGS, UGS, geological carbon storage, and UHS. These criteria cover various aspects, including reservoir performance, legal access, regulatory compliance, economic viability, public acceptance, and safety and security considerations for storage sites (Figure 3). Users can evaluate each site using the proposed methodology and criteria, facilitating comparative analysis across multiple candidate sites (Figure 15).

While our report provides a broad overview of the site screening process without specifying particular use cases, we recognize the inherent challenge of establishing a universally applicable screening framework. Variations in available data and specific project requirements necessitate customization to geological, geographic, jurisdictional, and societal contexts. Therefore, our guidance serves as a flexible tool rather than a rigid template for site screening, emphasizing the importance of tailoring approaches to individual circumstances. As the site selection process progresses to more advanced stages, we advocate for the adoption of a comprehensive selection methodology that evolves with the increasing availability of detailed site data and integrates holistic evaluations such as reservoir performance assessments and economic analyses tailored to specific project needs.[4]

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Appendix A

Table A.1. Criteria from Hibbard and Gilfillan (2024).[79] Criteria are based on an in-depth understanding of existing primary research on H_2 storage.

Reservoir Property	Positive Indicators	Cautionary Indicators
Trap	Structural High relief	Stratigraphic Low relief
Caprock	Greater thickness than 100 m Past use for underground gas storage	Insecurity/leaking Faulting
Porosity, permeability	Past use for underground gas storage	
History	Depleted gas field	Depleted oil field Aquifer
Lithology	Sandstone Well sorted, uniform	Carbonate
Mineralogy	Feldspathic Quartz - rich	Clay cement Gypsum, anhydrite, pyrite
Depth		< 500 m
Temperature	>72°C <90°C	<30°C
Connate water & gas chemistry	High salinity (>2M NaCl)	CO_3^{2-}, SO_4^{2-} H_2S, S
Existing infrastructure	Cushion gas left in place Plugged and capped wells	Venting wells

Table A.2. Criteria from Thaysen et al. (2023).[9] The past use preference is based on the potential for three-phase (vs. two-phase) flow and residual hydrocarbons that can sustain microbial life in an oil field and nutrient replenishing in an aquifer. The SO_4^{2-} preference is based on a simulation study that found low microbial consumption of hydrogen (< 0.5 %) for a half year storage cycle with 1,250 mg/l SO_4^{2-}.

Property	Lower Risk		Higher Risk	
Past use	Gas field		Oil field, Aquifer	
SO_4^{2-} (mg/l)	<1,250		>1,250	
	No Risk	**Low Risk**	**Medium Risk**	**High Risk**
Salinity (M NaCl)	n.a.	n.a.	>1.7	n.a.
Temp (Celsius)	>122	>90	>55	<55

Table A.3. Criteria from Okoroafor et al. (2022).[10] Depth preference is based on the observation that at deeper depths, productivity decreases and compression costs increase.

Property	Disqualifying	1	2	3	4	5 (best)
Pressure	Wellhead Pressure constraint > Reservoir top pressure – 0.01 bar/m	>220 bar	160-220 bar	80-160 bar	50-80 bar	<50 bar
Flow capacity (permeability x thickness)		<1,000 mDm	1,000-10,000 mDm	10,000-40,000 mDm	>10,0000 mDm	40,000-10,0000 mDm
Volume at standard temperature and pressure		<12 km^3	12-120 km^3	120-600 km^3	600–1,200 km^3	>12,000 km^3
Reservoir dip			0-5 deg	>15 deg	10-15 deg	5-10 deg
Permeability anisotropy		>0.8		0.5-0.8		0.1-0.5
Permeability heterogeneity (ratio of permeability of top layer to permeability of layer that follows)		<1		>1		1
Reservoir structure		Flat		Anticlinal / moderately dipping (<5 deg)		Steeply dipping (>5 deg)
Geothermal gradient		>40 °C/km		20-40 °C/km		<20 °C/km
Depth	>3,000 m					~500 m
Permeability	<50 mD					
Porosity	<10%					
Reservoir thickness	<10 m					
Seal thickness	<20 m					
Secondary seal	None					
Faulting	4-km-wide “buffer zone” quaternary faults (USGS definition of an active fault zone)					
Resource in reservoir	Oil or gas condensate					Dry gas
Earthquake record	10 km diameter for M>5 (1969-present) 5 km diameter for M <5 (2015-present)					

Table A.4. Criteria from Reveillere and Gallo (2023).[57]

	Property	Proposed Criteria	Explanation	Location	Capacity	Performance
Reservoir geometry	Minimum reservoir top depth	500 m	Below typical grid pressure if above	N/A	2	1
	Maximum reservoir top depth	2,500 m	Max. depth is a CAPEX (e.g., drilling cost), OPEX (e.g., compression), and equipment standard question (e.g., wellhead grades at 6,000 psi)	N/A	2	1
	Closure / spill point	Min. height of 20 m	Preferably and not flat: dipping average of the structure value is important	N/A	3	2
	Closed area	Minimum 0.3 km^2	Underground storage gets interesting from a sufficient size only	N/A	3	1
	Thickness	Should be identified and documented across the proposed area	This should be known for depleted fields; for aquifers it may in a first approach be based on regional knowledge	N/A	2	1
	Type of trap	Must be identified and documented across the proposed area	Exclusion can be released with additional exploration. When possible, please estimate degree of additional exploration required	N/A	3	3
Reservoir petrophysics	Knowledge of the depositional environment	Must be identified and documented across the proposed area	Exclusion can be released with additional exploration. When possible, please estimate degree of additional exploration required	N/A	3	1
	Effective porosity	Minimums: Carbonates: 5 % Sandstones: 10%	Useful information: average and range values for each rock type; porosity type	N/A	2	1
	Permeability	Minimums: Carbonates: 10 mD Sandstones: 50 mD	Useful information: average and range for each rock type and associated porosity types	N/A	N/A	2
	Rock types & mineralogy	Must be identified and documented across the proposed area	Lithology preferred: homogeneous sandstone and carbonate. Avoid sulphide and disulphide if possible; mineralogical composition is required (e.g., avoid pyrite)	N/A	N/A	1
Reservoir tectonics	Tectonics events: main faults and their continuities	Availability of information across the proposed area	Required to assess the integrity of the containment, e.g., types of faults	N/A	2	2
	Connection: fault networks, fractures, corridors	Availability of information across the proposed area	e.g., compartmentalization of the reservoir	N/A	N/A	2
Reservoir fluids	In situ fluid (gas oil, water)	Availability of information across the proposed area	Preferred depleted gas field	N/A	2	2
	Initial pore pressure	Availability of information across the proposed area	Must be identified by proper exploration at some stage of the development, but can be estimated before	N/A	1	1

	Property	Proposed Criteria	Explanation	Location	Capacity	Performance
	Fluid temperature	Availability of information across the proposed area	Must be identified (notably for bacterial activity assessment) by proper exploration at some stage of the development, but can be estimated if necessary	N/A	1	1
	Type of aquifer and its hydrogeological activity	Availability of information across the proposed area	Must be identified at some stage. Usually available through regional scale context	N/A	3	3
	In situ fluid characteristics (density, viscosity, etc.)	Availability of information across the proposed area	Must be identified and documented in order to predict PVT exchange in the reservoir (native fluid and storage gas). Salinity, pH, ions composition, any info about bacteria, to predict microbiology reactions. Avoid CO_2, sulphurous or iron rich fluids	N/A	1	1
	Initial and current fluid contacts (depleted fields)	Availability of information across the proposed area	Must be identified and documented across the proposed area	N/A	1	1
	Production history	Knowledge of the various produced fluids		N/A	2	2
Geological context	Overlying strata	Must be identified and documented across the proposed area	Impact from and to neighboring activities	2	N/A	N/A
	Overlying aquifers	Must be identified and documented across the proposed area	Impact to drinking water aquifer or other conflict of uses	2	N/A	N/A
	Seismicity	Understanding / knowledge of local seismicity regime		2	N/A	N/A
Surface environment	Accessibility	Must be identified and documented across the proposed area		2	N/A	N/A
	Subsidence	Subsidence and its impacts are to be assessed		2	N/A	N/A
	Land ownership	Must have a possibility to secure		3	N/A	N/A
	Mining rights/regulatory compliance	Must be identified		3	N/A	N/A
	Acceptability	Public acceptance must be considered		3	N/A	N/A
1 = minor, 2 = major, 3 = exclusion criteria						

Table A.5. Criteria from Lemieux et al. (2020).[7] Depth preference is based on the depths where most current natural gas storage sites are found. Caprock thickness preference is based on experience with carbon capture and storage. Reservoir thickness, porosity, permeability, and salinity preferences are only intended to apply to saline aquifers.

Property	Exclusion
Depth	<400 m, >2,000 m
Proximity to infrastructure	Far
Proximity to populated areas	
Extent of existing geological characterization	Poorly characterized
Location	Offshore, remote/inaccessible location
Past use (extraction operations)	No; <75% recoverable resource extraction (gas); <50 % recoverable resource extraction (oil)
Caprock thickness	<20 m
Reservoir thickness	<20 m
Reservoir porosity	<10%
Reservoir permeability	<1 mD
Salinity	>10,000 mg/L total dissolved solids
Faults	Low risk
Seismicity	Low risk

Table A.6. Criteria from Tarkowski (2017).[54] Preferences are based on experience with CCS.

Property	Exclusion
For depleted oil and gas fields	
Depth	>2,000 m
Past use	None <50% recoverable resource extraction for oil <75% recoverable resource extraction for gas
Listed on the current inventory of mineral resources	No
For aquifers	
Depth	>2,000 m
Caprock thickness	<50 m

Table A.7. Criteria from Lewandowska-Śmierzchalska et al. (2018).[11]

Property	1 (worst)	3	5	7	9 (best)
Seal lithology	Sandstones, limestones, dolomites	Clayey sandstones, limestones, dolomites	Interbedded sandstones, siltstones, mudstones	Mud stones, mud shales	Claystone, clay shales, Ca – sulphate rocks, salt rocks
Tectonic activity	Faults go into reservoir overburden	Faults ending in reservoir	Numerous faults in basement	Single faults in basement	Without faults
Deposit form	Oil				Gas

Table A.8. Criteria from Safari et al. (2023).[8] Formation rock type preference is based on the reactivity of certain mineralogies.

Property	Disqualifying	1	2	3	4	5
Depth	<1000 m or >3000 m	>3,000 m	3,000-2,000	2,000-1,500	1,500-1,300	1,300-1,000
Tectonic activity	Probabilistic seismic hazard index <6% (the likelihood that a specific site would experience ground motion intensity that exceeds a specified value within a certain time period)	>26%	6-26%	3-6%	0.1-3%	<0.1%
Access to LNG port	No port	>200 km	200-100 km	50-100 km	20-50 km	<20 km
Pressure	Wellhead pressure > reservoir pressure - 0.01 × true vertical depth	>220 bar	16-220 bar	80-160 bar	50-80 bar	<50 bar
Distance to capital of prefecture		>200 km	200-100 km	50-100 km	20-50 km	<20 km
Porosity	<10%	<10%		10-30%		>30%
Formation rock type	>10% carbonate minerals					
Reservoir thickness	<20 m					
Seal thickness	<10 m					
Resource in reservoir	Oil or gas condensate					Dry gas
Adjacent city	Within city boundary					
Restricted land/sensitive habitat	Within restricted/sensitive land					
Population density	> 75 person/km^2					
Access to pipeline	No access to pipeline					
Proximity to solar farm	No solar farm in adjacent prefectures					

Table A.9. Criteria from Cavanagh et al. (2022).[80] Depth and permeability preferences are based on properties of existing natural gas storage sites. Salinity preference is based on microbial risks and well scaling risks. Stratigraphy preference is based on reservoir modelling ease and predictability.

	Property	**Positive**	**Negative**
Practical parameters	Depleted gas field	Yes	No
	Cushion gas in place	Yes	No
	Low well remediation costs	Yes	No
	Prior history of usage	Yes	No
	Proximity to network	Yes	No
	Similarity to nearby natural gas storage	Yes	No
	Availability for development	Yes	No
Physical parameters	Depth	500-2,500 m	<500 m
	Permeability	20-2,000 mD	<20 mD
	Porosity	10-30 %	<5 %
	Reservoir thickness	10-200 m	<10 m
	Salinity	30-300 g/l	<15 g/l
	Stratigraphy	Simple	Complex
	Working gas ratio	0.3-0.7	> 0.9

Table A.10. Criteria from Juez-Larré et al. (2019).[81] Permeability preference is based on the permeability at which stimulation might be required to make a viable reservoir. Gas initially in place (GIIP) preference is based on the large cushion gas requirements and geologic complexity of large fields.

Property	**Exclusion**
Developed and accessible through production wells at the time of evaluation	No
Depth	<1,000 m
H_2S	>=10,000 ppm
Permeability	<=0.1 mD
Used currently for storage	Yes
Gas initially in place (GIIP)	>30,000 MMm^3
Initial well deliverability	<1 MMm^3/day
Flow capacity	<=100 mDm

Table A.11. Additional criteria suggested by the literature but not used in a site-selection framework. For each risk, general findings and extent of resource loss are reported in the top row. Then, specific studies and the criteria they inform are displayed in the rows that follow.

<table>
<tr><td colspan="4">Geochemical reactions
Generally, abiotic geochemical reactions are shown to consume little hydrogen but could have a significant effect on reservoir porosity and permeability in carbonates. The most common mineral changes are carbonate and gypsum cement dissolution/precipitation. These reactions may increase in significance with temperature. Sandstone/silica shows little to no reactivity.
<u>Extent of resource loss</u>: No significant reactions or resource loss in sandstone.[59] Minimal resource loss, but significant porosity decrease (8%), in carbonates.[60]</td></tr>
<tr><td colspan="4">Gholami (2023)[64]
Investigates geochemical reactions between H_2 and sandstone reservoirs at reservoir conditions through modeling.</td></tr>
<tr><th>Property</th><th>Lower Risk</th><th>Higher Risk</th><th>Comments</th></tr>
<tr><td>Minerology</td><td>Calcite, anhydrite, gypsum-poor</td><td>Calcite, anhydrite, gypsum-rich</td><td>Calcite precipitation (and pore volume changes), and anhydrite/gypsum dissolution (and formation of H_2S) are two most prominent geochemical reactions</td></tr>
<tr><td>Salinity</td><td><100,000 ppm NaCl (1.711 M NaCl)</td><td>> 100,000 ppm NaCl (1.711 M NaCl)</td><td>Scaling (salt precipitation) begins after 10 years</td></tr>
<tr><td colspan="4">Hassanpouryouzband et al. (2022)[59]
Experimentally investigates ~250 batch reactions at different reservoir conditions, using ~6 sandstone samples. Most sandstones were aeolian and one was fluvial.</td></tr>
<tr><th>Property</th><th>Lower Risk</th><th>Higher Risk</th><th>Comments</th></tr>
<tr><td>Temperature</td><td><90°C</td><td>>90°C</td><td></td></tr>
<tr><td colspan="4">Al - Yaseri et al. (2023)[60]
Experimentally investigates geochemical reactions between H_2 and carbonate reservoirs at reservoir conditions.</td></tr>
<tr><th>Property</th><th>Lower Risk</th><th>Higher Risk</th><th>Comments</th></tr>
<tr><td>Minerology</td><td>Calcite-poor</td><td>Calcite-rich</td><td></td></tr>
<tr><td colspan="4">Microbial reactions
Generally, microbial reactions can pose a significant threat to H_2 storage systems. Studies show that microbial reaction risk decreases with increasing temp, pressure, salinity, and less sulfur, iron, and carbon-containing minerals.
<u>Extent of resource loss</u>: Minimal (0.01-1.3 % H_2 consumed) resource loss reported by modeling and field experience to very significant (32.9%, 40%, 17% H_2 consumed) resource loss reported by experimental work and field experience.[52, 62, 63]</td></tr>
</table>

<table>
<tr><td colspan="4">Thaysen et al. (2021)[16]: Uses an in-depth understanding of hydrogenotrophic bacteria and their growth requirements. Understanding inherently limited by those that can be cultivated in the lab.
Berta et al. (2018)[82]: Laboratory experiments using sediment-filled columns, groundwater percolation, and 2-15 bar H_2 partial pressures.</td></tr>
<tr><th>Property</th><th>Lower Risk</th><th>Higher Risk</th><th>Comments</th></tr>
<tr><td>Minerology</td><td>Sulphur, iron, carbon-containing minerals – poor</td><td>Sulphur, iron, carbon-containing minerals – rich</td><td rowspan="8"></td></tr>
<tr><td rowspan="2">Salinity</td><td>> 4.5 M NaCl or</td><td rowspan="2">Low</td></tr>
<tr><td>> 1.5 M NaCl w/ high temp</td></tr>
<tr><td rowspan="2">Temperature</td><td>> 122°C or</td><td rowspan="2">Low</td></tr>
<tr><td>> 75°C w/high salinity</td></tr>
<tr><td>Salinity</td><td>35 g/L</td><td></td></tr>
<tr><td>pH</td><td><5-8></td><td>>5-8<</td></tr>
<tr><td colspan="4">Multiphase fluid flow
Generally: H_2 trapping decreases with decreasing pressure because of increasing water contact angles (less water wet). However, this also means that H_2 structural trapping decreases.
<u>Extent of resource loss reported</u>: 43% H_2 trapped (unrecoverable) (this might only be relevant for first injection cycle, or on the edge of the plume)</td></tr>
<tr><td colspan="4">Thaysen et al. (2022)[59]
Experimentally investigates H_2 flow (imbibition/drainage) and displacement in a sandstone core.</td></tr>
<tr><th>Property</th><th>Lower Risk</th><th>Higher Risk</th><th>Comments</th></tr>
<tr><td>Pressure</td><td>2 MPa (20% H_2 trapped)</td><td>7 MPa (43% H_2 trapped)</td><td>This might be most prevalent for first injection cycle and/or on the edge of the plume</td></tr>
<tr><td colspan="4">Iglauer et al. (2020)[83]
Experimentally investigates H_2 wettability in sandstone</td></tr>
<tr><th>Property</th><th>Lower Risk</th><th>Higher Risk</th><th>Comments</th></tr>
<tr><td>Pressure</td><td>Low</td><td>High</td><td rowspan="2">They conclude that it “would be safer to avoid intermediate-wet conditions to ensure safe hydrogen storage.” H_2 wetness increases with increasing temperature and pressure in sandstone</td></tr>
<tr><td>Temperature</td><td>Low</td><td>High</td></tr>
<tr><td colspan="4">Hosseini et al. (2022)[84]
Experimentally investigates H_2 wettability in carbonates</td></tr>
<tr><th>Property</th><th>Lower Risk</th><th>Higher Risk</th><th>Comments</th></tr>
<tr><td>Pressure</td><td>Low</td><td></td><td rowspan="4">They find a calcite-rich rock can become H_2 wet at risky conditions, whereas a sandstone can only become intermediate-wet</td></tr>
<tr><td>Temperature</td><td>High</td><td></td></tr>
<tr><td>Salinity</td><td>Low</td><td></td></tr>
<tr><td>Minerology</td><td></td><td>Calcite-rich</td></tr>
</table>

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