Research, Society and Development, v. 13, n. 8, e5513846130, 2024
(CC BY 4.0) | ISSN 2525-3409 | DOI: http://dx.doi.org/10.33448/rsd-v13i8.46130

# Defining geological viability criteria for $CO_2$ and hydrogen storage in depleted oil and gas fields

## Definindo critérios de viabilidade geológica para armazenamento de $CO_2$ e hidrogênio em campos de petróleo e gás esgotados

## Definiendo criterios de viabilidad geológica para el almacenamiento de $CO_2$ e hidrógeno en campos de petróleo y gas agotados

Received: 06/05/2024 | Revised: 07/15/2024 | Accepted: 08/10/2024 | Published: 08/15/2024

**Mariana Ciotta**
ORCID: https://orcid.org/0000-0001-7873-7473
University of São Paulo, Brazil
E-mail: mariana.ciotta@usp.br
**Colombo Celso Gaeta Tassinari**
ORCID: https://orcid.org/0000-0003-0200-2889
University of São Paulo, Brazil
E-mail: ccgtassi@usp.br

**Abstract**
This study focuses on how depleted oil and gas fields can be used as geological reservoirs to support the shift towards decarbonization and sustainable, low-carbon energy systems. These reservoirs, integral to $CO_2$ and hydrogen storage, are pivotal in harmonizing the dual objectives of environmental conservation and energy transition. We delve into the characteristics of these depleted fields, evaluating their suitability for both $CO_2$ and hydrogen storage, each serving distinct yet complementary decarbonization roles. $CO_2$ storage, facilitated through carbon capture and storage (CCS) technology, aims to diminish atmospheric $CO_2$ levels, thereby mitigating climate change. In parallel, hydrogen storage in these depleted fields emerges as a strategic solution for managing the intermittency of renewable energy sources like wind and solar power. Our study starts from the premise of using depleted oil and gas fields, assessing their potential and challenges for $CO_2$ and hydrogen storage. We define essential criteria for evaluating the feasibility of depleted reservoirs, considering the distinct nature of $CO_2$ and hydrogen. The literature review supported the analysis developed in this research, leading to the creation of three categories of criteria — structural and tectonic, storage and containment, and impact and reactivity — which provide a comprehensive framework for evaluating the viability of these reservoirs for both gases. Through this perspective, this research aims to systematically assess how specific factors such as porosity and permeability impact the efficacy of gas storage, thereby identifying essential parameters for optimizing storage solutions for either $CO_2$ or hydrogen.
**Keywords:** Hydrogen storage; $CO_2$ storage; Depleted oil and gas fields; Geological storage; Geological reservoirs.

**Resumo**
Este estudo foca em como campos de petróleo e gás esgotados podem ser usados como reservatórios geológicos para apoiar a transição para sistemas de energia sustentáveis e de baixo carbono. Esses reservatórios, fundamentais para o armazenamento de $CO_2$ e hidrogênio, são essenciais para harmonizar os objetivos duplos de conservação ambiental e transição energética. Investigamos as características desses campos esgotados, avaliando sua adequação para o armazenamento tanto de $CO_2$ quanto de hidrogênio, cada um desempenhando papéis de descarbonização distintos, porém complementares. O armazenamento de $CO_2$, facilitado pela tecnologia de captura e armazenamento de carbono (CCS), visa diminuir os níveis de $CO_2$ atmosférico, mitigando assim as mudanças climáticas. Em paralelo, o armazenamento de hidrogênio nesses campos esgotados surge como uma solução estratégica para gerenciar a intermitência de fontes de energia renovável como eólica e solar. Nosso estudo parte do princípio do uso dos campos, avaliando seu potencial e desafios para o armazenamento de $CO_2$ e hidrogênio. Definimos critérios essenciais para avaliar a viabilidade desses reservatórios esgotados, considerando a natureza distinta do $CO_2$ e do hidrogênio. A revisão da literatura apoiou a análise desenvolvida nesta pesquisa, levando à criação de três categorias de critérios — estruturais e tectônicos, armazenamento e contenção, e impacto e reatividade — que fornecem uma estrutura abrangente para avaliar a viabilidade desses reservatórios para ambos os gases. Com essa perspectiva, esta pesquisa tem como objetivo avaliar sistematicamente como fatores específicos, como porosidade e permeabilidade, afetam a

eficácia do armazenamento de gás, identificando assim parâmetros essenciais para otimizar as soluções de armazenamento de $CO_2$ ou hidrogênio.
**Palavras-chave:** Armazenamento de hidrogênio; Armazenamento de $CO_2$; Campos de petróleo e gás esgotados; Armazenamento geológico; Reservatórios geológicos.

**Resumen**
Este estudio se centra en cómo los campos de petróleo y gas agotados pueden utilizarse como reservorios geológicos para apoyar la transición hacia sistemas energéticos sostenibles y de bajo carbono. Estos reservorios, fundamentales para el almacenamiento de $CO_2$ e hidrógeno, son cruciales para armonizar los objetivos duales de conservación ambiental y transición energética. Exploramos las características de estos campos agotados, evaluando su idoneidad para el almacenamiento tanto de $CO_2$ como de hidrógeno, cada uno desempeñando roles de descarbonización distintos pero complementarios. El almacenamiento de $CO_2$, facilitado por la tecnología de captura y almacenamiento de carbono (CCS), tiene como objetivo reducir los niveles atmosféricos de $CO_2$, mitigando así el cambio climático. Paralelamente, el almacenamiento de hidrógeno en estos campos agotados surge como una solución estratégica para gestionar la intermitencia de fuentes de energía renovable como la eólica y la solar. Nuestro estudio parte de la premisa de utilizar campos de petróleo y gas agotados, evaluando su potencial y desafíos para el almacenamiento de $CO_2$ e hidrógeno. Definimos criterios esenciales para evaluar la viabilidad de estos reservorios agotados, considerando la naturaleza distintiva del $CO_2$ y el hidrógeno. La revisión de la literatura apoyó el análisis desarrollado en esta pesquisa, llevando a la creación de tres categorías de criterios — estructurales y tectónicos, almacenamiento y contención, e impacto y reactividad — que proporcionan un marco integral para evaluar la viabilidad de estos reservorios para ambos gases. Desde esta perspectiva, esta investigación pretende evaluar sistemáticamente cómo factores específicos como la porosidad y la permeabilidad influyen en la eficacia del almacenamiento de gas, identificando así parámetros esenciales para optimizar las soluciones de almacenamiento, ya sea de $CO_2$ o de hidrógeno.
**Palabras clave:** Almacenamiento de hidrógeno; Almacenamiento de $CO_2$; Campos de petróleo y gas agotados; Almacenamiento geológico; Reservorios geológicos.

## 1. Introduction

As the world commits to decarbonization goals to combat climate change, geological reservoirs emerge as central in the transition to sustainable, low-carbon energy systems (Stephenson et al., 2019). This study focuses on depleted oil and gas fields, which offer a dual solution: $CO_2$ storage through carbon capture and storage (CCS) technology to reduce atmospheric $CO_2$ levels and hydrogen storage to manage the intermittency of renewable energy sources such as wind and solar power (Osman et al., 2022; Sorai et al., 2022; Tarkowski et al., 2021). While each storage method serves a distinct purpose —$CO_2$ storage aims at climate change mitigation by sequestering carbon, and hydrogen storage facilitates energy security by buffering renewable energy supply — their integration into geological formations underscores a shared commitment to decarbonization.

Reusing depleted oil and gas fields for $CO_2$ and hydrogen storage is a key strategy in combating climate change and transitioning to sustainable energy systems (Lysyy et al., 2021; Wei et al., 2023). As we strive to meet decarbonization targets, the ability of these reservoirs to effectively sequester carbon and store renewable energy not only aids in reducing atmospheric $CO_2$ levels but also addresses the intermittency of renewable energy sources. Moreover, deactivated oil and gas fields are efficient due to existing geological knowledge and infrastructure, which reduces costs and enhances the sustainability of the process (Janjua & Khan, 2023; Muhammed et al., 2023).

Effective $CO_2$ and hydrogen storage requires a thorough understanding of the geological properties of potential reservoirs, including porosity, permeability, and cap rock integrity, to ensure the long-term containment of these gases (Tarkowski, 2019; Tomić et al., 2018). However, challenges such as potential gas leakage, reactions with surrounding materials, and the economic feasibility of extraction and storage technologies must be addressed to realize their full potential (Li and Liu, 2016; Uliasz-Misiak et al., 2021).

The storage of $CO_2$, through CCS technology, aims to reduce the atmospheric concentration of this gas, thereby mitigating the impact of climate change (Bui et al., 2018; Metz et al., 2005). This process involves capturing $CO_2$ emissions from industrial processes and power generation, followed by their secure storage in geological formations such as depleted oil and gas fields, deep saline aquifers, or unmineable coal seams (Cachola et al., 2023). The effectiveness of $CO_2$ storage hinges on the reservoir's ability to retain the gas over extended periods, necessitating a comprehensive understanding of the reservoir's geological properties, including its porosity, permeability, and cap rock integrity.

On the other hand, hydrogen storage in geological formations is emerging as a key strategy in managing the intermittency of renewable energy sources like wind and solar power (Hassanpouryouzband et al., 2021). By storing excess energy in the form of hydrogen, these reservoirs can act as large-scale energy storage systems, ensuring a steady supply of energy during periods of low renewable energy production. The suitability of a geological formation for hydrogen storage depends on factors such as its ability to prevent hydrogen escape, minimize reactivity with surrounding materials, and allow for efficient recovery (Amid et al., 2016).

This study explores the potential of using depleted oil and gas fields reservoirs for $CO_2$ and hydrogen storage, critical for a sustainable and adaptable energy future. We assess these reservoirs' suitability by comparing the geological storage requirements for $CO_2$ and hydrogen, aiming to enhance their use in energy transition and climate change mitigation. This analysis emphasizes the shared decarbonization goals and addresses the unique challenges and opportunities of utilizing depleted oil and gas fields, offering practical insights for optimizing geological formations toward a cleaner, more sustainable future.

## 2. Theoretical Background

This literature review focuses on the geological storage of hydrogen and $CO_2$, which is essential for energy transition and decarbonization. We examine current research and practices in geological storage, highlighting the stage of development and the potential for overcoming technological challenges. This review aims to present a concise overview of the field's progress and future directions.

$CO_2$ storage research is further along due to its thematic maturity and the execution of pilot projects, indicating significant advancements in carbon capture and sequestration technologies (Bashir et al., 2024; Cao et al., 2020). In 2005, the Intergovernmental Panel on Climate Change (IPCC) released a technical report on carbon capture and storage technologies, and since then, several advances have been made in the scientific, technical, economic, and policy dimensions of this technology (Metz et al., 2005). Moreover, the International Energy Agency (IEA) estimates that by 2050, CCS could account for a reduction of nearly 19% in global $CO_2$ emissions (IEA, 2024). Globally, CCS technology has been advancing since the inception of the first facility, the Terrell Natural Gas Processing plant in Texas, in 1971 (Loria and Bright, 2021). Over its initial four decades, the expansion of CCS initiatives experienced fluctuating progress. Yet, the last ten years have seen a significant surge in the development of CCS projects, with the planned capacity for CCS nearly doubling in just the last three years (Loria and Bright, 2021). In 2023, 198 new facilities have been added to the development pipeline, bringing the current total to 41 projects in operation, 26 under construction, and 325 in advanced and early development (Global CCS Institute, 2023).

Research into underground hydrogen storage is in the early stages, with limited practical experience and few industrial examples. However, growing interest suggests that technological and other challenges will likely be overcome shortly (Tarkowski, 2019). Identifying suitable sites for such storage necessitates a comprehensive geological assessment, focusing on a range of critical characteristics, including the depth, thickness, and integrity of the geological structures, as well as their tectonic stability, hydrogeological and geothermal properties, and the reservoir's capacity for pressure, porosity, and permeability (Olabi et al., 2021). Moreover, the rock's mechanical properties and the cap rocks' quality are crucial for ensuring safe and efficient hydrogen containment. The efficiency of underground hydrogen storage systems typically ranges between

30% and 40%, with potential improvements of up to 50% achievable through the advancement of technologies (Matos et al., 2019). While aboveground storage solutions tend to limit hydrogen gas pressure to below 100 bar due to the cost and material requirements of the storage containers, underground options allow for pressures up to 200 bar, offering a higher storage density of approximately 7.8 kg/m³ at 100 bar and 20°C (Witkowski et al., 2017). This distinction underscores the economic advantage of underground storage, particularly for large-scale applications, due to the significantly lower investment and operational costs compared to aboveground storage.

Globally, the potential for underground hydrogen storage has been recognized and explored in various regions. For instance, studies in France have evaluated the prospects of utilizing different underground formations, such as depleted oil fields, aquifers, and salt caverns, for hydrogen storage, with a particular emphasis on salt deposits for their favorable cycling performance and capacity requirements (Olabi et al., 2021). Similarly, the UK and the USA have confirmed the feasibility of storing substantial quantities of hydrogen in salt cavities. Northern Germany, with its accessible salt caverns meeting specific geological criteria, and Scotland, with identified hydrogen storage potentials in different geological groups, exemplify the European commitment to harnessing underground storage. Romania and Poland have also identified potential sites for hydrogen storage, highlighting a broad interest and the geographical diversity of research into underground hydrogen storage solutions (Iordache et al., 2014; Tarkowski, 2017).

This evolution in hydrogen storage reflects a growing acknowledgment of the need for scalable, efficient, and secure storage solutions as part of the broader transition toward sustainable energy systems. The exploration of underground storage facilities across different geological settings demonstrates the global effort to integrate hydrogen as a key component of future energy landscapes, offering a path forward for large-scale energy storage and a move toward decarbonization.

When $CO_2$ and hydrogen are geologically stored, they behave differently due to their distinct properties (Table 1). $CO_2$, being denser, tends to remain more stable under geological conditions, especially when injected into deep saline formations or depleted oil and gas fields. It can also react with minerals to form stable carbonates over time, enhancing its storage security (Zhang and DePaolo, 2017). Hydrogen, however, is lighter and requires careful consideration of its potential to migrate through geological formations. Its small molecule size poses a challenge for containment, making the selection of suitable geological formations critical for preventing leakage and ensuring long-term storage. Additionally, hydrogen is highly flammable and explosive, posing a significant safety hazard if leaked (Jeon and Kim, 2020). This risk makes stringent containment and safety protocols essential during compression and storage. Compressing these gases is necessary for efficient storage due to their voluminous nature. Hydrogen, with a molecular weight of 2.016 g/mol, contrasts sharply with carbon dioxide, which is 22 times heavier. At standard conditions (20°C and 1 atm), carbon dioxide's density far exceeds hydrogen's (Vargaftik, 1975). Carbon dioxide also displays the highest critical density, significantly greater than hydrogen, underscoring the distinct storage requirements for each gas.

**Table 1 -** Overview of the physicochemical characteristics of hydrogen and $CO_2$. Based on (SpringerMaterials, 2024a, 2024b).

| Properties | Hydrogen | $CO_2$ |
|---|---|---|
| Molecular mass (g/mol) | 2.016 | 44.009 |
| Density at NTP (kg/m$^3$) | 0.08375 | 1.842 |
| Dynamic viscosity at 20 °C (10−5 Pa S) | 0.88 | 1.47 |
| Gas constant (J/kg K) | 4124.2 | 188.92 |
| Specific gravity (air = 1) (−) | 0.07 | 1.52 |
| Critical temperature (°C) | −239.96 | 31.06 |
| Critical pressure (bar) | 13.13 | 73.83 |
| Critical density (kg/m$^3$) | 31.43 | 468.19 |
| Solubility in water (g/100 g) | 0.00016 | 0.169 |
| Net heating value (MJ/kg) | 120–141.7 | – |

Source: Authors.

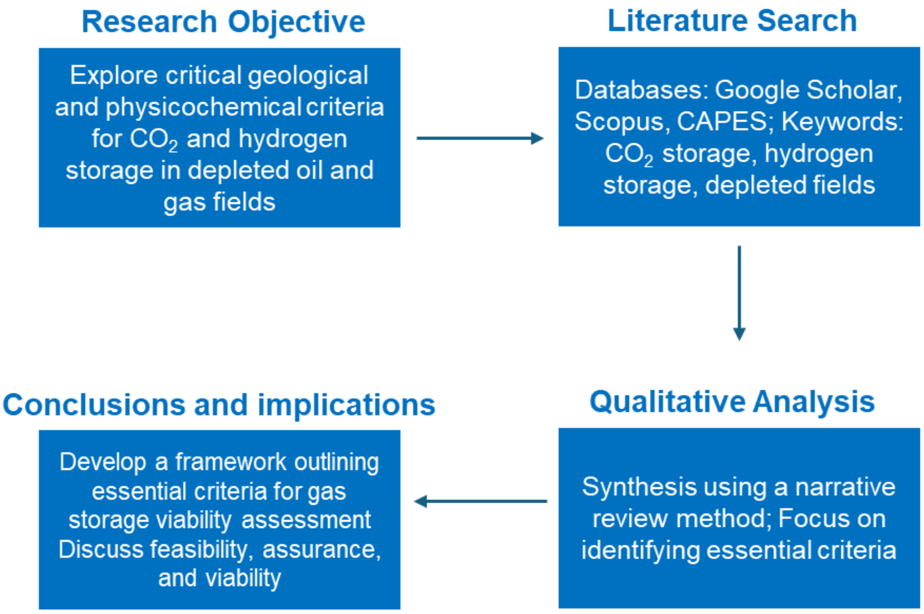
Decommissioning can be understood as the process of disposal of the equipment used in offshore oil production and safe plugging of the hole in the earth's surface (Osmundsen and Tveterås, 2003). Leveraging decommissioning processes as an opportunity for environmental stewardship, particularly through the implementation of $CO_2$ and hydrogen storage in depleted oil and gas fields, presents a cost-effective and strategic approach to decarbonization. The integration of gas storage into the decommissioning strategy capitalizes on the unique geological properties conducive to gas retention, emphasizing the economic and environmental benefits. This approach not only utilizes existing infrastructure but also addresses the necessity for safe and efficient gas containment, advancing global environmental conservation efforts and supporting a seamless transition to sustainable energy systems.

The literature highlights the critical role of enhancing geological storage technologies for $CO_2$ and hydrogen in global efforts towards decarbonization. $CO_2$ storage has made considerable advancements, and hydrogen storage is rapidly evolving, crucial for integrating renewable energy into sustainable systems. The focus on depleted oil and gas fields is particularly important due to their established geological understanding and existing infrastructure, offering a streamlined and cost-effective approach to storage. Addressing the specific challenges of safely and efficiently storing each gas is vital for their role in environmental conservation and energy transition.

## 3. Methodology

This study employed a narrative review methodology to systematically assess the critical geological and physicochemical criteria necessary for $CO_2$ and hydrogen storage in depleted oil and gas fields (Figure 1). We conducted a narrative literature review, as this approach is well-suited for exploratory studies that aim to provide a broad understanding of a field without the strict methodological constraints of systematic reviews. This type of review allowed us to integrate information from various sources, including scholarly articles, geological reports, and case studies, to encapsulate emerging practices and challenges within the realm of gas storage. The narrative review methodology is supported by Mendes (2022), who elaborates on its utility for developing a comprehensive understanding of a subject through qualitative synthesis of existing literature.

**Figure 1** – Methodological framework. Source: Authors (2024).




Source: Authors.

The articles and reports for this study were sourced from multiple databases including Google Scholar, Scopus and the CAPES periodicals database, ensuring a comprehensive collection of relevant literature. Key terms used in our searches included "$CO_2$ storage," "hydrogen storage," "depleted oil and gas fields," "porosity," "permeability," and "geological surveys." These keywords were chosen to specifically target articles that discuss the physicochemical and geological aspects of gas storage in depleted reservoirs. Each article was evaluated based on its relevance to our research questions, which were focused on identifying the essential geological and physicochemical criteria necessary for effective gas storage. Our analysis involved qualitative synthesis of the data, informed by the critical insights from leading research in the field, which provided empirical support for identifying vital parameters like lithology, trapping mechanisms, and petrophysical properties.

This research aims to study how specific factors such as porosity and permeability impact the efficacy of gas storage, thereby identifying essential parameters for optimizing storage solutions for either $CO_2$ or hydrogen. Initially, a review of scholarly articles, geological reports, and case studies was conducted to grasp these fields' complex dynamics and capabilities. This qualitative exploration shed light on diverse perspectives and emerging practices and encountered challenges within the realm of gas storage, providing invaluable insights into the non-quantifiable aspects of field suitability. Subsequently, the study leveraged data on critical geological factors such as porosity, permeability, and other salient properties essential for effective gas storage. Sources for this data included detailed geological surveys, comprehensive reservoir analyses, and accessible public databases, ensuring a solid empirical foundation underpinning our qualitative observations.

In addressing the geological prerequisites for $CO_2$ and hydrogen storage, the study delineates essential criteria such as lithology, trapping mechanisms, and petrophysical properties, informed by the intended storage duration (short-term vs. long-term). This comprehensive evaluation, informed by leading research (Hu et al., 2023; Zhong et al., 2024), underscores the pivotal role of geological criteria in determining storage feasibility, containment assurance, and project viability.

From the gathered literature, we developed a framework that outlines the essential criteria for assessing the viability of $CO_2$ and hydrogen storage in depleted fields. This framework is crucial for understanding the interplay between various geological factors and their impact on storage efficacy, informed by both our narrative review and empirical data from geological surveys and reservoir analyses. This research enhances the dialogue surrounding sustainable energy solutions, focusing on strategically repurposing depleted fields for energy transition initiatives. Central to this study is the objective to establish criteria that will subsequently facilitate the analysis of viability for $CO_2$ and hydrogen storage, underscoring the vital role of meticulously chosen parameters in optimizing the utility of these fields for sustainable storage solutions.

## 4. Geological Criteria for $CO_2$ and Hydrogen Storage

In this article, following an extensive literature review, we propose categorizing geological criteria into three main groups based on their functions and importance in the context of $CO_2$ and hydrogen storage in depleted oil and gas fields. Additionally, it's pertinent to consider the storage purpose to better understand the geological criteria for storage selection. Therefore, it's necessary to delineate whether the storage is intended for the short or long term, as different lithologies and trapping mechanisms may suit each case (Zhong et al., 2024). From this, it becomes necessary to characterize geological requirements, such as conditional petrophysical properties and key trapping mechanisms (Hu et al., 2023; Zhong et al., 2024).

It's worth noting that operating with depleted oil and gas fields as a concept can be challenging due to their varied geological premises. Oil and gas fields are not a unified geological formation, so understanding the specifics of each field's unique geological composition is crucial. These differences complicate efforts to standardize the criteria for evaluating the suitability of depleted fields. Thus, it is essential to accurately characterize each field's lithology, structural features, and trapping mechanisms. This section examines key geological criteria for $CO_2$ and hydrogen storage, focusing on a range from the most general to the most specific aspects:

1. Structural and Tectonic Criteria:

a. Tectonic Stability: The absence of significant tectonic plate movements that could affect the integrity of the reservoirs.

b. Geological and Structural History: Past and present geological characteristics influencing the viability of fields for storage.

2. Storage and Containment Criteria:

c. Porosity and Permeability: These are fundamental characteristics affecting storage capacity and the mobility of $CO_2$ and hydrogen within the reservoir.

d. Cap Rock Integrity: The cap rocks' ability to prevent leakage and ensure long-term containment.

e. Solubility and Adsorption: The dissolution behavior of $CO_2$ and hydrogen in reservoir fluids and their adsorption on rock surfaces, influencing storage effectiveness.

f. Interfacial Tension (IFT): Affects the migration and trapping mechanisms within the reservoir, enhancing the mobility of gases, which impacts storage processes.

g. Wettability: Influences how gases interact with the reservoir rock surfaces, affecting the distribution and movement of gases within the reservoir.

h. Diffusion: Due to its high diffusivity, diffusion is critical for understanding the movement of gas molecules within the reservoir, particularly hydrogen.

3. Impact and Reactivity Criteria:

i. Chemical Reactivity and Mineralization: The potential for chemical reactions between stored gases and reservoir minerals, including the capacity for $CO_2$ mineralization. Total Organic Carbon (TOC) analysis is essential for assessing the presence of residual hydrocarbons and organic material, which can affect gas storage by interacting with injected gases and influencing storage security.

j. Seismicity Induction Risk: Assessment of the risk that storage activities might trigger seismic events.

These criteria, from porosity and permeability to tectonic stability, gas solubility, reservoir rock properties, interfacial tension, and adsorption, offer a structured approach to assessing geological formations for $CO_2$ and hydrogen storage. They highlight the importance of understanding both the broad and specific geological aspects that contribute to the effectiveness and safety of gas storage in depleted fields.

## 5. Results

The following sections will present the results of our analysis, shedding light on the significance of each criterion within its category. By addressing the structural and tectonic conditions that underpin the integrity and stability of potential storage sites, the intrinsic properties such as porosity and permeability that govern storage capacity and fluid mobility, and the reactivity and impact considerations that ensure the long-term safety and environmental compliance of storage operations, this part of the study aims to provide a detailed insight into the geological prerequisites for effective $CO_2$ and hydrogen storage.

### 5.1 Structural and Tectonic Criteria

The structural and tectonic criteria encompass the foundational aspects of geological formations that are essential for determining the viability of depleted oil and gas fields for $CO_2$ and hydrogen storage. This section delves into the importance of tectonic stability and geological history, focusing on the absence of significant tectonic plate movements and the historical geological characteristics that influence a field's suitability for storage. By examining these structural and tectonic factors, we aim to underscore their critical role in ensuring the integrity of potential storage reservoirs, thereby minimizing risks associated with geological instabilities and ensuring the long-term success of storage projects.

#### 5.1.1 Tectonic stability

Tectonic stability, defined as the absence of significant movements of tectonic plates over time in a specific region, is crucial for safely and effectively storing $CO_2$ and hydrogen in geological reservoirs (Liu et al., 2023; Tilford et al., 1983). Tectonic stability impacts the storage of these gases since it influences the structural integrity of the geological formations where the gases are stored. Regions with high tectonic stability typically have more cohesive geological formations, reducing the likelihood of fractures or faults that could compromise containment. Additionally, areas with minimal tectonic activity are preferred to minimize the risk of induced seismic events triggered by gas injection or extraction activities, thus enhancing storage safety (Sapiie et al., 2015). Overall, selecting sites with tectonic stability is essential for ensuring the long-term integrity and sustainability of $CO_2$ and hydrogen storage projects, facilitating efficient containment, and mitigating environmental risks.

Incorporating detailed geotechnical surveys and geological mapping is essential to enhance the understanding of tectonic stability in the context of $CO_2$ and hydrogen storage. These tools are critical for evaluating potential sites by detecting hidden faults, understanding stress fields, and assessing the mechanical properties of rock formations. Historical geodata on tectonic movements and seismic activity also play a significant role, offering a deeper historical perspective that aids in predicting future geological behavior and designing effective mitigation strategies (Wang et al., 2015). Furthermore, understanding the relationship between tectonic stability and existing hydrocarbon fields is crucial, especially for depleted fields where previous extraction activities might influence current geomechanical stability (Zhu et al., 2018). This connection highlights the need for an in-depth analysis of how tectonic forces might affect the integrity of cap rocks over time, which are vital for maintaining the seal and preventing the escape of stored gases.

Additionally, discussing long-term monitoring and management plans that address potential tectonic changes can demonstrate proactive risk management, including the installation of seismic monitoring equipment and the periodic reassessment of tectonic stability (Priolo et al., 2015). Including case studies where tectonic stability was a critical factor in the success or failure of geological storage projects could provide real-world examples, offering valuable lessons and best practices. By weaving these elements into the discussion, the narrative on tectonic stability becomes not only more comprehensive and informative but also practically oriented towards improving the planning and execution of geological storage projects for $CO_2$ and hydrogen.

#### 5.1.2 Geological and Structural History

A site's geological and structural history plays a pivotal role in assessing its suitability for $CO_2$ and hydrogen storage. This criterion involves a thorough investigation into the past and present geological characteristics of potential storage fields, focusing on aspects such as the age of the rocks, the types of rock formations, the history of geological events, and the evolutionary changes these formations have undergone over geological time scales. Understanding the geological history helps identify the types of rocks that make up the reservoir and cap rock, their permeability, porosity, and how these properties have been altered by geological processes such as sedimentation, metamorphism, and erosion.

Similarly, the structural history provides insights into the deformation patterns within the reservoir, including faulting and folding patterns. These structural features can significantly impact the mechanical stability of a reservoir and its ability to contain gases (Al-Kindi and Richard, 2014). For example, regions with extensive faulting might be prone to leakage pathways for $CO_2$ or hydrogen, whereas tightly folded structures might offer natural barriers to gas migration (Wang et al., 2015).

The evaluation of geological and structural history is critical for understanding current reservoir conditions and assessing the broader petroleum system within which these geological formations exist. The petroleum system concept integrates the source rocks, migration pathways, reservoir rocks, trap mechanisms, and seals that control the accumulation and preservation of hydrocarbons. In the context of $CO_2$ and hydrogen storage, similar principles apply, where the integrity of the seal (cap rock), the quality of the reservoir rock, and the efficacy of the trap mechanisms are crucial for effective gas containment.

By examining the geological and structural history, we can predict potential challenges in gas storage such as the risk of leakage through undetected faults or fractures and the effectiveness of the cap rock as a seal (Arnold et al., 2019). Incorporating detailed geological surveys, seismic imaging data, rock mechanics studies, and an understanding of the associated petroleum system into the evaluation process enriches the understanding of the site-specific geological context, helping to optimize the storage design to suit the unique characteristics of each field.

The geological reservoirs and petroleum systems play distinct roles in influencing the storage of $CO_2$ and hydrogen due to the different properties of these gases. $CO_2$, being denser and heavier, requires robust reservoir and seal integrity, as it can chemically react with minerals in the formation, potentially leading to mineralization that could strengthen the rock matrix but also necessitate stable geological conditions for long-term containment. The effectiveness of $CO_2$ storage is also heavily dependent on the historical migration pathways within the petroleum system, which, if not properly mapped and sealed, could become leakage paths. On the other hand, hydrogen, with its small molecular size and high diffusivity, presents unique challenges in storage. It can escape through smaller spaces more easily than $CO_2$, making structural integrity crucial. Hydrogen does not react chemically with reservoir rocks or fluids under typical conditions, which minimizes concerns about rock alteration but also eliminates the security provided by mineral trapping, relying more on the physical containment capabilities of the geological structures (Heinemann et al., 2018; Liu et al., 2022).

Temperature and pressure are also key factors influencing the properties and behavior of $CO_2$ and hydrogen in storage, as they directly determine the phase, density, and mobility of these gases within geological reservoirs (Nielsen et al., 2012). At varying temperature and pressure combinations, $CO_2$ can exist in gaseous, liquid, or supercritical states, each with unique storage implications. Supercritical $CO_2$, which has the density of a liquid but the mobility of a gas, is particularly advantageous for geological storage due to its efficient space utilization (Khudaida and Das, 2020). Pressure and temperature also affect its reactivity with reservoir minerals, potentially forming stable carbonates that strengthen containment or causing mineral alteration that could weaken storage integrity. In contrast, hydrogen remains gaseous in most geological conditions but is highly sensitive to pressure and temperature (Liang et al., 2017). Higher pressures and temperatures increase hydrogen's diffusivity and mobility, heightening its potential to migrate through rock formations and posing leakage risks (Perera, 2023). This necessitates the selection of reservoir rocks and cap rocks that are impervious to hydrogen escape and can withstand the combined effects of pressure and temperature over time. Overall, the interplay between temperature, pressure, and the properties of these gases defines the efficiency and security of storage strategies, underscoring the need for precise geological assessments and reservoir design tailored to their specific behaviors.

Integrating these gases into storage strategies requires a nuanced understanding of each gas's behavior under specific geological conditions shaped by their respective histories. For $CO_2$, strategies focus on leveraging its chemical reactivity to enhance containment security through mineral trapping, whereas for hydrogen, the emphasis is on ensuring that the geological formations are capable of physically containing the gas without significant losses. This tailored approach, informed by detailed geological and structural histories and an understanding of the broader petroleum system, is crucial for developing effective and environmentally sustainable storage solutions. Both gases necessitate strategic planning that considers the current geological makeup of potential storage sites and their evolutionary geological histories to mitigate risks and enhance the efficacy of storage projects.

### 5.2 Storage and Containment Criteria

The criteria for storage and containment address the physical and chemical properties of geological formations that directly impact the storage capacity and the effectiveness of $CO_2$ and hydrogen containment. This section explores the pivotal roles of porosity and permeability in determining a reservoir's ability to store significant quantities of gases and the integrity of cap rocks in preventing gas leakage. Additionally, the solubility and adsorption characteristics of $CO_2$ and hydrogen in reservoir fluids and rock surfaces are examined for their influence on enhancing storage security and efficiency.

#### 5.2.1 Porosity

Porosity is a key factor in evaluating the suitability of a depleted oil and gas field for $CO_2$ and hydrogen storage, standing as one of the most straightforward properties of reservoir rocks (Badawy and Ganat, 2022a; Bagdassarov, 2021). It is essential for reservoir studies and hydrogen storage since it dictates fluid flow and transport within geological formations and affects the overall properties of rocks. Porosity itself is relatively easy to define — it represents the measure of empty space within a rock, defined as the ratio of pore volume (PV) to bulk volume (BV) of the rock, typically expressed as a fraction or percentage and serves as a scalar dimensionless variable, often changing linearly — but quantifying it accurately is challenging due to the wide range of void space scales present in earth materials (Anovitz and Cole, 2015; Badawy and Ganat, 2022a).

$$\Phi = \frac{PV}{BV} \tag{1}$$

The porosity present during the initial deposition of rock is termed primary porosity. This encompasses inter-granular porosity in sandstones and inter-crystalline porosity in carbonates. Conversely, additional porosity resulting from subsequent geological processes constitutes secondary porosity, notably seen in fractures across various rock types and solution cavities within carbonates. Secondary porosity tends to be more prevalent in carbonate and basement reservoirs, with fractures often being the primary voids in basement reservoirs. It's worth noting that a rock dominated by primary porosity typically exhibits greater homogeneity compared to one dominated by secondary porosity (Badawy and Ganat, 2022a).

Absolute or total porosity is the straightforward measure obtained from the basic definition, representing the total void space within a rock. On the other hand, effective or interconnected porosity accounts for the volume of interconnected void space specifically, as per the definition given. In the basic definition, this effective porosity can be calculated by replacing the pore volume (PV) with the volume of interconnected void space.

$$\Phi_e = Interconnected \frac{PV}{BV} \quad (2)$$

Reservoir rock porosity plays a vital role in estimating hydrocarbon reserves and determining the hydrocarbon in place, which is essential to understanding the storage capacity of a given reservoir. Therefore, it determines the volume of gas that can be stored since high porosity reservoirs are preferable as they offer larger storage capacities (Tarkowski, 2019; Tarkowski et al., 2021). However, the reservoir rock should be overlapped by a lower porosity rock, to ensure the permanence of the gas by avoiding potential leakages (Shukla et al., 2010; Verga, 2018). Rocks initially possess inherent primary porosity, which can be further modified by processes like deformation and fracturing.

Understanding porosity is crucial for assessing the suitability of geological formations for $CO_2$ and hydrogen storage, as it directly influences storage capacity and transport properties within the rock matrix. Interconnected pores are essential for effective storage, ensuring that the stored gas remains trapped within the rock formation and does not leak out. Hydrogen has a higher diffusion rate than $CO_2$, meaning it can migrate more easily through interconnected pore networks. Rocks with well-connected pore networks and higher porosity are therefore desirable for hydrogen storage as they facilitate the movement and distribution of the gas within the rock formation. However, excessive porosity or large pore sizes can also pose challenges for gas storage, as they may increase the risk of gas leakage or migration. Therefore, the ideal $CO_2$ and hydrogen storage porosity characteristics involve a balance between sufficient void spaces for storage and effective trapping mechanisms to prevent gas escape.

In summary, the porosity of rocks significantly impacts the storage of gases such as $CO_2$ and hydrogen, with higher porosity generally offering greater storage capacities. However, the interconnectedness of pores and the trapping mechanisms within the rock formation are crucial factors determining gas storage operations' effectiveness and safety.

**5.2.2 Permeability**

The permeability of a rock dictates its ability to transmit fluids, such as $CO_2$ and hydrogen, through its pore network (Badawy and Ganat, 2022b). For effective $CO_2$ and hydrogen storage, a reservoir must have adequate permeability to allow for the injection and containment of these gases. It is typically expressed in units of darcies (D) or millidarcies (mD), representing the ease with which fluids can flow through the rock matrix. Unlike porosity, which measures the void space within a rock, permeability quantifies the ability of fluids to move through that void space. In terms of a horizontal cylindrical sample of a porous material, Darcy's Law can be expressed as follows in c.g.s. units:

$$Q = \left(\frac{KA}{\mu}\right)\left(\frac{\Delta P}{\Delta L}\right) \quad (3)$$

where,

Q = Flow rate, cc/s

A = Cross sectional area of the sample, $cm^2$

μ = Fluid Viscosity, poises

P = Pressure Difference (P1−P2), dyne/ $cm^2$

L = Length of the sample, cm

K = Constant (Later defined as the porous medium permeability).

Analysis of Darcy's law reveals that permeability (K) is dimensionally equivalent to area, allowing it to be expressed in any area unit. Initially, Darcy defined permeability in square centimeters, which was later deemed impractical for industry use due to its large magnitude (Badawy and Ganat, 2022b). Consequently, the adopted industry standard for permeability measurement is the darcy, where 1 darcy equals $9.869 \times 10^{-9}$ square centimeters or $1.062 \times 10^{-11}$ square foot. The darcy represents the permeability of a fully saturated porous medium with a single fluid of 1.0 centipoise viscosity, permitting the flow of that fluid at a rate of 1.0 cubic centimeter per second per square centimeter under a pressure gradient of 1.0 atmosphere per centimeter. However, the more commonly used practical unit in industry is the millidarcy, equivalent to 0.001 darcy (Badawy and Ganat, 2022b).

The permeability of a porous medium, when fully saturated with a single fluid, is termed absolute permeability ($K_{abs}$), which remains consistent regardless of the saturating fluid. However, when multiple fluids saturate the medium, different permeability values emerge for each fluid, denoted as effective permeability to that specific fluid. For instance, in a medium containing oil, water, and gas, distinct effective permeabilities ($K_o$, $K_w$, and $K_g$) are assigned to each phase, with their sum being less than the absolute permeability ($K_o + K_w + K_g < K_{abs}$). It's essential to emphasize that permeability is an inherent property of the rock, making terms like "air permeability" or "oil permeability" misleading; instead, it's more accurate to refer to permeability to air or oil. Relative permeability to a specific fluid is the ratio of its effective permeability to the rock's absolute permeability, a value that varies with the fluid's relative saturation. Although permeability is a vector variable, showcasing different values across different directions, commonly simplified into horizontal ($K_h = K_x = K_y$) and vertical ($K_v = K_z$) permeabilities, such generalizations may not hold for reservoirs with high levels of anisotropy, where complexities in permeability distribution must be carefully considered.

Understanding permeability is crucial for assessing the suitability of geological formations for $CO_2$ and hydrogen storage, as it directly influences fluid flow and transport properties within the rock matrix. Rocks with higher permeability are preferable for gas storage, as they facilitate the movement and distribution of gases within the reservoir. However, excessive permeability can lead to unwanted gas leakage or migration, necessitating careful consideration of the ideal permeability characteristics for storage operations.

In practice, the permeability requirements for $CO_2$ and hydrogen storage are similar, yet differences in the properties of these gases can lead to subtle disparities. While both gases necessitate permeable pathways for efficient migration and distribution, variations arise due to their distinct characteristics. $CO_2$ storage relies on permeable routes to facilitate its movement within geological formations, with higher permeability enhancing storage capacity and containment efficiency. However, excessive permeability may pose risks of rapid migration and potential leakage, necessitating meticulous management strategies. Conversely, hydrogen storage demands effective containment within porous rock formations, where moderate permeability and well-connected pore networks are advantageous for facilitating gas migration and distribution. Nevertheless, excessive permeability can lead to accelerated gas loss and reduced storage efficiency, highlighting the importance of striking a balance between permeability and containment. Therefore, while the overall permeability requirements may align, the subtle differences in gas properties warrant careful consideration to optimize storage effectiveness and safety.

In summary, permeability is a fundamental parameter that significantly impacts the storage of gases such as $CO_2$ and hydrogen in geological formations. Higher permeability generally allows for greater fluid flow, but the interconnectedness of pore pathways and effective trapping mechanisms within the rock matrix are crucial factors that determine the effectiveness and safety of gas storage operations.

**5.2.3 Cap Rock integrity**

Cap rock integrity is a critical factor in the geological storage of $CO_2$ and hydrogen, primarily concerning the effectiveness of the seal provided by the cap rock to prevent gas leakage from the storage reservoir (Shukla et al., 2010). The cap rock is typically an impermeable layer, such as shale or salt, that sits atop more permeable reservoir rocks. Its main function is to act as a natural barrier that traps gases and fluids within the underlying reservoir formations, making its integrity vital for the long-term success and safety of gas storage projects. There are several complex interactions between cap rock and injected fluids (like $CO_2$-brine mixtures) under reservoir conditions. These interactions have profound implications on the cap rock's ability to act as an effective barrier against the upward migration of stored gases (Shukla et al., 2010).

The assessment of cap rock integrity involves several physical properties. The impermeability and thickness of the cap rock are primary concerns. These properties determine the cap rock's ability to prevent the vertical migration of gases. The mechanical strength of the cap rock also plays a crucial role, as it must withstand the pressures exerted by the injected gases without fracturing.

Especially relevant for $CO_2$ storage, the chemical interactions between the stored gas and the cap rock can affect its integrity. For instance, the injection of $CO_2$ can lead to acidification of pore fluids, potentially dissolving carbonate rocks or altering mineralogy. This chemical reactivity can weaken the cap rock structure, leading to increased porosity and permeability.

Ensuring cap rock integrity not only involves initial assessments but also continuous monitoring for potential changes in its properties over time. Prolonged dynamic contact between rock and fluid in conditions mimicking actual reservoir environments is essential for accurately predicting long-term cap rock behavior (Shukla et al., 2010). Techniques such as seismic imaging, pressure monitoring, and fluid sampling are used to detect signs of cap rock deterioration or leakage. If integrity issues are detected, remediation methods, including the injection of sealant materials or pressure management adjustments, may be implemented.

The integrity of the cap rock directly impacts the feasibility, safety, and public confidence in $CO_2$ and hydrogen storage projects (Safari et al., 2022). Effective management of cap rock integrity not only prevents environmental contamination and greenhouse gas emissions but also ensures the economic viability of the storage site by maintaining the stored gases securely. As such, rigorous assessment and continuous monitoring of cap rock integrity are integral components of any underground gas storage strategy.

**5.2.4 Solubility**

Solubility plays a significant role in the geological storage of both $CO_2$ and hydrogen. In the case of $CO_2$, solubility can lead to the gas being captured in various natural reservoirs, including remaining oil, formation water, and minerals. Through the solubility process, $CO_2$ is dissolved into fluids present in geological formations, thereby reducing its mobility and contributing to long-term containment (Ding et al., 2018). The solubility of $CO_2$ in formation water is influenced by factors such as pressure, temperature, and salinity, with the highest solubility coefficient observed at lower pressures. Additionally, the solubility coefficient of $CO_2$ in remaining oil is notably higher compared to formation water, in line with the principle of "like dissolves like" (Ding et al., 2018).

Similarly, in hydrogen storage, solubility is also crucial, particularly concerning the dissolution of hydrogen in groundwater or other fluids within the reservoir. This dissolution can help diminish the mobility of hydrogen and facilitate its retention underground (Chabab et al., 2020). Due to its high mobility and reactivity, hydrogen presents unique challenges for underground storage, particularly concerning its involvement in microbial processes such as sulfate reduction and methanogenesis. Understanding hydrogen's solubility in aqueous environments under varying thermodynamic conditions is crucial for effective storage management and safety (Chabab et al., 2020). The presence of salt in water decreases hydrogen solubility, a phenomenon known as the salting-out effect. Understanding how solubility impacts the behavior of these gases is essential for designing and implementing effective geological storage strategies.

### 5.2.5 Adsorption

Adsorption refers to the process by which a gas adheres to the surface of the rock. This is particularly relevant for hydrogen storage due to its small molecule size. Temperature and pressure exert significant effects on the adsorption behavior of $CO_2$. For $CO_2$, a concave downward parabolic relationship exists between the pressure and adsorption (Zhang et al., 2023). There are varied adsorption characteristics based on rock type, which is crucial for storage strategies in geological formations (Tajnik et al., 2013). For example, sandstone demonstrated significant adsorption capacity under controlled conditions, reflecting its potential for $CO_2$ sequestration (Tajnik et al., 2013). This capacity is influenced by the rock's physical properties such as porosity and mineral content, which can vary widely among different geological materials. The gravimetric method used in the investigations indicates that these capacities are also dependent on temperature and pressure, critical parameters that must be optimized to enhance the efficacy of $CO_2$ storage in various rock types.

In terms of pressure, while increasing pressure generally enhances the amount of gas that can be adsorbed, hydrogen, due to its low molecular weight and high diffusivity, does not adhere as strongly or as densely as $CO_2$ (Thomas, 2007). This behavior necessitates specialized storage considerations, particularly in ensuring the adsorption takes place at safe but effective pressures to prevent excessive leakage or safety hazards. In both cases, optimizing the adsorption process involves a deep understanding of the geological reservoir, including porosity, permeability, and mineral composition, as well as the physical behaviors of $CO_2$ and hydrogen under various pressure and temperature conditions.

### 5.2.6 Interfacial Tension (IFT)

IFT plays a significant role in the migration and trapping mechanisms of $CO_2$ and hydrogen in the reservoir. Lower IFT can enhance the mobility of these gases, which directly impacts the storage process, affecting how these gases distribute within the reservoir and their eventual trapping. The behavior of IFT under reservoir conditions provides insights into how effectively these gases can be stored and what strategies might be needed to optimize their containment (Chalbaud et al., 2009; Zhang and Wang, 2023).

For $CO_2$, the presence of the gas reduces IFT between the gas and the water, particularly under increased temperatures and pressures common in subsurface environments. This reduction in IFT enhances the mobility of $CO_2$, facilitating its distribution within the reservoir which can improve injection rates and the overall storage capacity. However, the effect of reduced IFT also raises considerations regarding the potential for leakage paths if the cap rock or other geological barriers are not sufficiently robust (Chalbaud et al., 2009).

In the case of hydrogen, the IFT dynamics are crucial for ensuring the gas is effectively contained within the reservoir. Hydrogen, with its smaller molecular size compared to $CO_2$, can be more challenging to contain due to its higher mobility. The molecular dynamics studies reveal that the interaction of hydrogen with cushion gases can lower the IFT, thereby requiring careful management to ensure that hydrogen does not escape the geological formations intended for its storage. Furthermore, the reduction of hydrogen self-diffusion at interfaces caused by the presence of $CO_2$ and $CH_4$ highlights the importance of these interactions in managing the subsurface behavior of hydrogen (Chang et al., 2024).

The addition of $CO_2$ as a cushion gas not only aids in reducing the IFT but also contributes to a decrease in the self-diffusion of hydrogen at the interface, which could be leveraged to enhance the stability and efficiency of hydrogen storage operations in geological formations. This nuanced understanding of gas-water IFT, particularly how it is influenced by temperature, pressure, and gas composition, is crucial for optimizing strategies for the long-term storage of $CO_2$ and the effective short-term storage of hydrogen in geological reservoirs.

**5.2.7 Wettability**

Wettability impacts how gases interact with the reservoir rock surfaces. It affects the distribution and movement of $CO_2$ and hydrogen within the reservoir. An analysis of the free energy change accompanying $CO_2$ adsorption on the rock surface shows that adsorbed $CO_2$ could result in moving the $CO_2$/water/rock contact line and change the rocks from water-wet to non-water-wet, increasing the potential for $CO_2$ to spread and displace water (Wang et al., 2023). $CO_2$ adsorption on rocks could decrease the capillary force in geological reservoirs and enable injected $CO_2$ to enter a greater portion of pore space. This would significantly increase the reservoir utilization efficiency and $CO_2$ storage capacity (Wang et al., 2023).

The wettability behavior of $CO_2$ can significantly vary across different minerals, such as quartz, calcite, and muscovite mica, under reservoir conditions (Farokhpoor et al., 2013). It highlights that factors such as pressure, temperature, and the presence of brine can influence the $CO_2$ contact angles on these minerals, thereby affecting how $CO_2$ is stored. For instance, at higher pressures, the $CO_2$ contact angle tends to increase, particularly near the critical pressure, indicating changes in $CO_2$'s compressibility and behavior near its critical state. These findings suggest that the geological storage of $CO_2$, particularly under conditions approaching supercritical $CO_2$, could be influenced by these wettability changes, affecting both the storage security and capacity (Farokhpoor et al., 2013).

Wettability plays a critical role in how hydrogen interacts with reservoir rock surfaces, affecting its distribution and movement within geological formations (Al-Yaseri et al., 2021). The study of hydrogen wettability on clay surfaces, particularly kaolinite, illite, and montmorillonite, highlights that these clays generally exhibit water-wet properties with contact angles below 40°, conducive to capillary and residual trapping of hydrogen in underground environments (Al-Yaseri et al., 2021).

The favorable water-wetting properties of these clays, particularly kaolinite with its hydrophilic octahedral sheet, suggest effective trapping mechanisms that could enhance the security and efficiency of hydrogen storage. Moreover, this water-wet behavior is crucial for the dynamics of hydrogen storage in subsurface environments, particularly because a water-wet system can enhance the capillary trapping of hydrogen, which is beneficial for its short-term storage (Higgs et al., 2022). Variations in pressure and salinity slightly influence these wettability characteristics, but the overall tendency towards water-wet conditions remains consistent across different experimental settings (Higgs et al., 2022). These findings are crucial for the design and optimization of underground hydrogen storage facilities, providing insights into the selection of geological formations based on their wettability characteristics and the potential for efficient hydrogen storage and retrieval.

The differing wettability characteristics between $CO_2$ and hydrogen have implications for their storage and mobility in geological reservoirs. $CO_2$'s ability to transition from water-wet to less water-wet upon adsorption enhances its spread and injectivity, allowing it to displace more formation water and occupy greater pore space, which is beneficial for efficient sequestration. In contrast, hydrogen's consistent water-wet nature leads to enhanced capillary trapping in smaller pore spaces, securing its containment but potentially limiting its mobility and complicating its extraction. These wettability properties necessitate tailored strategies for the effective management and recovery of each gas from subsurface storage.

#### 5.2.8 Diffusion

Diffusion, characterized as the movement of gas molecules within a reservoir, is critical for both $CO_2$ and hydrogen, particularly given hydrogen's high diffusivity. During geological storage, as $CO_2$ and hydrogen migrate, they form static retention areas in the reservoir's rock, such as dead-end fractures and pores, where mass transfer is primarily governed by diffusion (Chen et al., 2023). $CO_2$ diffusion, coupled with reaction processes, significantly influence its transport and the spatial-temporal distribution of resulting reactions, such as carbonate precipitation. Moreover, the presence of geochemical gradients, created by diffusion transport, can result in highly localized zones of carbonate precipitation, enhancing the effectiveness of $CO_2$ sequestration while potentially affecting the distribution of hydrogen within similar contexts (Chen et al., 2023). These processes ultimately alter the reservoir's properties by changing the distribution and concentration of minerals, which can affect long-term storage security and efficiency.

Molecular dynamics simulations have shown that the diffusion coefficient of $CO_2$ in saline water varies with temperature, pressure, and the concentration of dissolved salts. These variations influence the formation of viscous fingering and the onset of instabilities that can affect the overall storage mechanism (Omrani et al., 2022). Salinity plays a crucial role; as the concentration of salts like NaCl in the water increases, the $CO_2$ diffusion coefficient decreases. This is attributed to the formation of hydration shells around salt ions, which act as physical barriers to $CO_2$ movement, thereby reducing its mobility. This effect of salinity on diffusion highlights the complex interplay between geochemical conditions and $CO_2$ behavior in subsurface environments (Omrani et al., 2022).

Diffusion in hydrogen storage is impacted by its molecular properties and the conditions under which it is stored. Notably, hydrogen's high diffusivity means it can quickly spread throughout a storage facility, which requires careful management to ensure safety and efficiency. This property is particularly crucial during incidents of leakage where hydrogen can disperse rapidly, potentially leading to hazardous concentrations unless properly managed (Yang et al., 2024). Higher pressures and lower temperatures tend to increase the range and rate of hydrogen diffusion (Yang et al., 2021).

In summary, diffusion influences the storage approaches for $CO_2$ and hydrogen, but with distinct considerations for each gas. For $CO_2$, the diffusion process helps determine how effectively it can be stored, particularly influencing its ability to engage in long-term mineralization and dissolution processes. For hydrogen, its inherently high diffusivity necessitates stringent containment strategies to control its rapid spread and address safety concerns associated with potential leaks. Understanding and managing these diffusion characteristics are essential for developing effective and safe geological storage solutions for $CO_2$ and hydrogen.

### 5.3 Impact and Reactivity Criteria

Impact and reactivity criteria are focused on the potential interactions between stored gases and the surrounding geological environment, including the chemical reactivity and mineralization potential of $CO_2$, and the assessment of seismicity induction risk. This section highlights the importance of evaluating the potential for chemical reactions between stored gases and reservoir minerals, which can affect the stability and permanence of storage. Additionally, we address the risk assessment of storage activities potentially triggering seismic events, emphasizing the need for careful consideration of these aspects in the planning and monitoring of $CO_2$ and hydrogen storage projects. Understanding these criteria is essential for ensuring that storage does not adversely affect the geological environment or pose a risk to public safety.

#### 5.3.1 Chemical reactivity and mineralization

Chemical reactivity refers to the ability of substances to undergo chemical changes or reactions with other substances. In the context of geological storage, this concept is relevant for understanding how injected gases like $CO_2$ interact with the minerals found in geological formations. Mineralization is a specific type of chemical reaction where $CO_2$ reacts with minerals such as silicates to form stable, solid carbonate minerals like calcite ($CaCO_3$). Through mineralization, $CO_2$ is transformed from a gaseous state into a solid form that is locked away in the geological structure, effectively removing it from the atmospheric cycle. For hydrogen, however, the storage dynamics are quite different. Hydrogen does not typically participate in mineralization due to its chemical properties. Instead, the storage of hydrogen in geological formations relies more on physical methods, such as trapping the gas in porous rock structures or using the natural barriers of the geological formation to contain the gas. Unlike $CO_2$, hydrogen storage does not result in a permanent chemical transformation of the element; rather, it focuses on effectively containing the gas to prevent escape and ensure its availability for energy use.

Mineralization in the context of geologic carbon storage encompasses the transformation of $CO_2$ into stable carbonate minerals $(Ca,Mg,Fe)CO_3$ through chemical reactions with silicate minerals in the reservoir. The injected $CO_2$, compressed into a supercritical state at industrial sites, interacts with divalent cations released from the dissolution of silicate minerals, facilitated by the acidified pore fluid within the reservoir (Zhang and DePaolo, 2017). This transformation is seen as the most secure and permanent form of carbon sequestration, ensuring the long-term immobilization of carbon away from the atmospheric cycle.

The rate of mineralization is influenced by several factors, including the mineralogy of the reservoir rock, which determines the abundance of necessary divalent cations and the kinetics of their release into the solution. These kinetics are affected by the pH, fluid flow rate, and the presence of dissolved $CO_2$ (Matter et al., 2016). Despite the wide range of observed rates of transformation, spanning eight to ten orders of magnitude in laboratory and field observations, reservoir-scale reactive transport simulations have refined these estimates. These simulations suggest that under conditions such as pH levels between 4.5 and 6, fluid flow velocities under 5 meters per year, and timeframes extending 50 to 100 years post-injection, the mineralization process can be more precisely predicted. They estimate that 60-90% of the injected $CO_2$ could be converted into carbonate minerals within 200 to 2000 years, provided the reservoir rock contains a sufficient volume fraction (about 20% by volume) of reactive silicate minerals (Zhang & DePaolo, 2017).

The presence of organic matter can influence the chemical reactions involving $CO_2$ within the reservoir. Organic materials can react with injected $CO_2$, potentially affecting the rate and extent of mineralization processes. Depending on the nature of the organic matter and the conditions within the reservoir, these reactions can either facilitate or hinder the transformation of $CO_2$ into stable mineral forms. In experimental studies involving high-TOC shales treated with $CO_2$, findings indicate that the reactivity of $CO_2$ with these types of rocks can lead to minor alterations in mineral composition and slight changes in the dissolution behavior of minerals like calcite (Fatah et al., 2024). For instance, the presence of $CO_2$ can enhance the solubility of carbonates in shales, which might contribute to mineralization processes that serve as efficient long-term $CO_2$ trapping mechanisms.

In the case of hydrogen storage, however, the situation varies significantly, and the circumstances of containment and confinement are quite different compared to $CO_2$ storage. The process of mineralization, in turn, typically does not play a directly analogous role. Effective hydrogen storage often relies on barriers to movement within the stratigraphic system, given that the molecular properties of hydrogen—being light and small—facilitate its diffusion through containment materials or interaction with structural traps differently. The challenges of forming stable mineral phases from hydrogen are substantially greater, with considerations for practical storage focusing more on conversion, dissolution, or adsorption rather than direct chemical reactions leading to mineral formation (Pan et al., 2021; Perera, 2023).

In essence, the pathways for mineralization, particularly in the context of hydrogen storage, do not involve the straightforward formation of stable mineral phases as part of the storage process, as is the case with $CO_2$ where the gas reacts with water-bearing minerals to form carbonate minerals. Instead, discussions about the geological storage of hydrogen revolve around concepts like containment, permeability, and the transfer of mass, considering the different reactive pathways and facilitators for gas movement and interaction with geological media. This emphasizes the reliance on engineered barriers and a nuanced understanding of geological and hydrological conditions, leading to variable implications for the efficiency and feasibility of mineralization as a storage strategy.

The lack of mineralization in hydrogen storage is actually advantageous because the intention behind hydrogen storage is not for long-term containment but rather for its use as a flexible energy carrier. This distinct characteristic of hydrogen storage aligns with the energy sector's need for renewable energy sources that can be rapidly mobilized to meet fluctuating demands. Unlike $CO_2$, where permanent sequestration is sought to mitigate climate change impacts by removing carbon from the atmosphere indefinitely, hydrogen serves as a key component in energy systems, requiring retrievability to supply fuel cells, power generation, and other energy conversion processes when needed.

The convenience of non-mineralization for hydrogen lies in the preservation of its gaseous state, facilitating its extraction and mobilization from storage sites. This approach supports the dynamic use of hydrogen as an energy vector, allowing it to be stored during periods of surplus renewable energy production and then retrieved to provide energy when renewable sources are insufficient. The reversible nature of hydrogen storage, without the complications of mineralization, enables a more efficient and responsive energy storage system, crucial for balancing energy grids and supporting the transition to a more sustainable and resilient energy infrastructure. This reversibility is key to hydrogen's role in energy systems, where it can act as a buffer to accommodate the intermittency of renewable energy sources and help reduce dependence on fossil fuels. Therefore, the non-mineralization of hydrogen not only suits its intended use but also enhances the flexibility and efficiency of energy storage and distribution systems, making it a crucial component of future energy strategies.

**5.3.2 Seismicity Induction Risk**

Seismicity induction risk refers to the potential for man-made activities, such as the injection of gases into geological formations, to trigger seismic events or earthquakes. This risk is a significant concern in the geological storage of gases like $CO_2$ and hydrogen, where the alteration of subsurface pressures and the mechanical disturbances caused by injection can potentially activate nearby faults or create new fractures. For $CO_2$ storage, the high volumes and pressures involved increase the likelihood of inducing seismic events, which can compromise the storage site's integrity and lead to the stored gas's leakage (Cheng et al., 2023).

Hydrogen storage, while generally associated with lower seismic risks due to typically lower pressures used, still requires careful consideration of geological conditions, especially if storage sites are located near fault lines or in areas with a history of seismic activity. Managing these risks involves thorough geological assessments and monitoring to ensure the stability and safety of the storage operations for both types of gases. A preliminary numerical assessment focused on the deformation of a three-dimensional fault extending from the reservoir into the caprock during hydrogen injection and storage provides valuable insights into this issue (Burtonshaw et al., 2022).

Post-injection observations are crucial for understanding the long-term behavior of $CO_2$ and hydrogen in depleted reservoirs (Mito and Xue, 2011). While both $CO_2$ and hydrogen geological storage can induce seismicity, the mechanisms and risks associated differ due to the nature of the gases and their interaction with geological environments.

## 6. Discussion

This study has examined the potential of depleted oil and gas fields as viable reservoirs for $CO_2$ and hydrogen storage, highlighting their dual role in both climate change mitigation and energy transition. Our analysis reveals that while these geological formations present unique opportunities due to existing infrastructure and known geological properties, there are significant challenges that must be addressed to optimize their use for gas storage.

We have identified that $CO_2$ and hydrogen behave differently within geological storage due to their distinct physical and chemical properties. For $CO_2$, its higher density and reactivity with mineral substrates provide opportunities for both structural and mineral trapping. However, these reactions can also pose risks to cap rock integrity over time, potentially leading to leakage if not properly managed. In contrast, hydrogen, with its low density and non-reactivity, poses a greater challenge in terms of physical containment, requiring robust cap rock integrity and careful management of underground movement.

Our findings underscore the critical importance of cap rock integrity for both types of storage. The mechanical and chemical stability of cap rocks determines the long-term success of underground gas storage. For $CO_2$, ensuring that the cap rock can withstand acidification processes without degrading is crucial. For hydrogen, the focus is on ensuring that the cap rocks are free from micro-fractures through which hydrogen could escape, given its small molecule size.

The absence of significant tectonic movements is crucial for ensuring the integrity of the reservoirs. Geologically stable fields present a lower risk of disruptions that could facilitate gas leakage. Understanding the historical and current geological characteristics of the fields is essential for assessing their suitability for storage. The rock formations should possess features that favor long-term gas containment, such as adequate porosity and an absence of significant fractures. Porosity and permeability are fundamental for storage capacity and the mobility of $CO_2$ and hydrogen within the reservoir. Adequate porosity and permeability are necessary for effective injection and safe retention of gases. The cap rock must maintain exceptional integrity to prevent leaks and ensure the long-term containment of the stored gases.

Particularly for $CO_2$, it can react with minerals in the reservoir to form stable carbonates, a process known as mineralization, which aids in secure long-term containment. For hydrogen, chemical reactivity is less of a concern, but its high diffusivity requires robust physical barriers. Both gases can alter subsurface pressures and potentially induce seismic activities. It is vital to assess and manage this risk, especially in geologically sensitive areas.

While $CO_2$ and hydrogen storage share certain geological requirements for successful implementation, their distinct physical and chemical properties lead to notable differences in their storage mechanisms. Both types of storage necessitate geologically stable fields to minimize the risk of disruptions that could facilitate gas leakage, and both require reservoirs with specific geological characteristics such as adequate porosity and impermeable cap rocks to ensure safe and effective containment.However, the similarities in their storage requirements extend to the need for precise management of induced seismic risks, as the injection of either gas can alter subsurface pressures and potentially activate fault lines. Effective management of these risks is critical to prevent seismic events that could compromise the integrity of the storage sites.

On the other hand, the differences between $CO_2$ and hydrogen storage are pronounced in their interaction with the geological environment. $CO_2$'s ability to react with minerals in the reservoir to form stable carbonates — a process known as mineralization — provides a unique mechanism for long-term containment by chemically binding the $CO_2$ within the rock formations. This mineralization process not only secures the stored $CO_2$ but also potentially enhances the mechanical strength of the reservoir.

In contrast, hydrogen does not typically undergo mineralization due to its non-reactive nature. Instead, the primary challenge in hydrogen storage arises from its high diffusivity, requiring the maintenance of exceptionally robust physical barriers to prevent the gas from escaping through micro-fractures in the cap rock. This necessitates a focus on different aspects of geological suitability, including the structural integrity of the containment system and the engineering solutions designed to mitigate hydrogen's propensity to diffuse.

In summary, while both $CO_2$ and hydrogen storage technologies rely on similar geological foundations for successful storage — such as stable geological formations and capable cap rock integrity — their methods of interacting with these formations and the strategies required to ensure their effective containment differ, fundamentally reflecting the unique physical and chemical behaviors of each gas.

Incorporating these criteria into the planning and management of geological storage of $CO_2$ and hydrogen in depleted oil and gas fields is essential to maximize effectiveness and minimize risks. A detailed understanding of geological properties and continuous monitoring of reservoir conditions is crucial to ensure that storage is not only efficient but also safe and sustainable over the long term.

Table 2 presents a compilation of the key geological viability factors for $CO_2$ and hydrogen storage in depleted oil and gas fields. It categorizes these factors into structural and tectonic, storage and containment, and impact and reactivity criteria, detailing their specific impacts on each type of gas storage. This comprehensive overview facilitates a clear understanding of how different geological properties influence the effectiveness and security of storing these gases. For each criterion, the table illustrates how the properties affect $CO_2$ and hydrogen differently, such as the significant role of cap rock integrity in preventing leakage and the varied importance of solubility and adsorption between the two gases. This organized format aids in quickly identifying targeted strategies for enhancing storage safety and efficiency, tailored to the unique characteristics of $CO_2$ and hydrogen.

(CC BY 4.0) | ISSN 2525-3409 | DOI: http://dx.doi.org/10.33448/rsd-v13i8.46130

**Table 2 -** Comparative analysis of geological viability criteria for $CO_2$ and hydrogen storage in depleted fields. Source: Authors (2024).

| Criteria category | Specific criteria | Impact on $CO_2$ storage | Impact on hydrogen storage |
|---|---|---|---|
| **Structural and Tectonic** | Tectonic Stability | Key to $CO_2$ storage, ensuring the long-term integrity of the containment and minimizing the risk of environmental hazards by preventing fractures and faults that could lead to leaks and induced seismic events. | Critical in safeguarding against rapid gas migration and escape, maintaining cap rock integrity to prevent leaks, and enhancing the overall safety and sustainability of storage sites. |
| | Geological and Structural History | Affects choice of storage based on past stability, ensuring that the denser gas can be effectively contained and mineralized within stable geological formations, which are crucial for mitigating leakage and enhancing long-term storage. | Influences suitability and risk of leakage, which is crucial for hydrogen storage to navigate its high diffusivity and ensure that smaller molecular spaces are securely sealed, preventing escape through undetected faults or compromised cap rocks. |
| **Storage and Containment** | Porosity | Determines the storage capacity and efficacy of containment within geological formations, ensuring that the gas is securely trapped and the risk of leakage minimized. | Interconnectedness of porosity is essential, facilitating the distribution and movement of the highly diffusive gas while also highlighting the need for precise control to prevent escape through porous networks. |
| | Permeability | Dictates storage flow within the reservoir, serving as a critical determinant for optimizing $CO_2$ storage capacity and mitigating leakage risks within geological formations. | Critical for controlling diffusion and distribution. |
| | Cap Rock Integrity | Ensures effective containment and preventing gas leakage, with chemical interactions posing critical considerations for long-term stability and safety. | Essential for long-term containment (despite high diffusivity), maintaining secure containment, preventing gas migration, and safeguarding the viability and safety of storage sites, necessitating rigorous assessment and continuous monitoring measures. |
| **Storage and Containment** | Solubility | Influences gas containment by facilitating its dissolution into fluids within geological formations, thereby reducing mobility and enhancing long-term containment. | Poses distinct issues for geological storage due to its high mobility and reactivity, especially given its role in microbiological processes like sulfate reduction and methanogenesis. It is essential to comprehend hydrogen's solubility in aqueous environments under a range of thermodynamic settings for safe and efficient storage management. |
| | Adsorption | Affects how $CO_2$ interacts and stabilizes within the reservoir fluids and is influenced by factors like pressure and rock type. | Although pressure affects adsorption, its low molecular weight necessitates specialized considerations to ensure safe and effective containment within geological reservoirs. |

| | | | |
|---|---|---|---|
| | Interfacial Tension (IFT) | Influences gas mobility and distribution within the reservoir, affecting injection rates and storage capacity, albeit raising concerns about potential leakage pathways if geological barriers are insufficiently robust. | IFT management is critical for containing the gas effectively within reservoirs, especially considering its higher mobility compared to $CO_2$, necessitating careful strategies to mitigate escape risks and optimize storage efficiency. |
| | Wettability | Alters the distribution and movement of $CO_2$ within geological reservoirs, with adsorption altering rock surfaces to enhance spread and increase reservoir utilization efficiency. | Water-wet properties facilitate capillary trapping, ensuring secure containment but potentially limiting mobility and extraction, highlighting the need for tailored strategies in subsurface storage management. |
| | Diffusion | Governs the spatial distribution and transport of $CO_2$ and hydrogen within geological reservoirs, impacting sequestration efficacy through geochemical reactions and mineral distribution. | High diffusivity poses safety challenges, necessitating precise containment strategies to mitigate rapid dispersion and potential hazards, highlighting the need for tailored approaches in subsurface gas storage management. |
| **Impact and Reactivity** | Chemical Reactivity and Mineralization | Chemical reactivity drives mineralization processes, transforming $CO_2$ into stable carbonate minerals for long-term immobilization. | Mineralization is not a primary mechanism, with containment strategies focusing on physical methods due to hydrogen's molecular properties. |
| | Seismicity Induction Risk | Significant concern regarding seismicity induction risk due to the potential for high volumes and pressures involved in injection activities, which can compromise site integrity and lead to gas leakage. | Careful consideration of geological conditions is required to mitigate seismic risks, highlighting the importance of thorough assessments and monitoring for ensuring storage safety and stability. |

Source: Authors.

## 7. Final Considerations

This study offers a comprehensive assessment of depleted oil and gas fields for their potential use in $CO_2$ and hydrogen storage, with a particular focus on the geological aspects that determine their suitability. Through analysis of structural and tectonic integrity, storage and containment properties, and the impact and reactivity of these geological formations, we have delineated the crucial factors that contribute to the effectiveness and safety of these storage methods. Our findings emphasize the significance of geological knowledge in optimizing the use of these fields for sustainable energy storage solutions.

1. Depleted fields with stable geological structures are more suitable for storage, as they are less likely to undergo significant tectonic movements that could compromise the integrity of the storage site.
2. The porosity and permeability of the reservoir rocks, along with the integrity of the cap rocks, are fundamental to ensuring that $CO_2$ and hydrogen are effectively contained. Cap rocks must be robust enough to prevent leakage and withstand potential degradation over time due to the stored gases.
3. $CO_2$'s interaction with reservoir rocks can lead to mineralization, which may enhance storage security but also poses a risk to the structural integrity of the reservoir over the long term. Hydrogen's non-reactivity, while minimizing chemical risks, requires stringent containment measures due to its small molecule size and high diffusivity.

In conclusion, while depleted oil and gas fields offer a promising avenue for $CO_2$ and hydrogen storage, their success hinges on a deep understanding of geological characteristics and a proactive approach to managing the associated risks. Future research should continue to refine our understanding of these complex interactions to ensure that this potential is fully realized in a safe and economically viable manner.

## Acknowledgments

This work was partially financed by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES).

## References

Al-Kindi, M. H., & Richard, P. D. (2014). The main structural styles of the hydrocarbon reservoirs in Oman. *Geological Society, London, Special Publications*, *392*(1), 409–445. 10.1144/SP392.20

Al-Yaseri, A., Wolff-Boenisch, D., Fauziah, C. A., & Iglauer, S. (2021). Hydrogen wettability of clays: Implications for underground hydrogen storage. *International Journal of Hydrogen Energy*, *46*(69), 34356–34361. 10.1016/j.ijhydene.2021.07.226

Amid, A., Mignard, D., & Wilkinson, M. (2016). Seasonal storage of hydrogen in a depleted natural gas reservoir. *International Journal of Hydrogen Energy*, *41*(12), 5549–5558. 10.1016/j.ijhydene.2016.02.036

Anovitz, L. M., & Cole, D. R. (2015). Characterization and Analysis of Porosity and Pore Structures. *Reviews in Mineralogy and Geochemistry*, *80*(1), 61–164. 10.2138/rmg.2015.80.04

Arnold, D., Demyanov, V., Rojas, T., & Christie, M. (2019). Uncertainty Quantification in Reservoir Prediction: Part 1—Model Realism in History Matching Using Geological Prior Definitions. *Mathematical Geosciences*, *51*(2), 209–240. 10.1007/s11004-018-9774-6

Badawy, A. M., & Ganat, T. A. A. O. (2022a). *Permeability* (pp. 35–56). 10.1007/978-3-030-87462-9_5

Badawy, A. M., & Ganat, T. A. A. O. (2022b). *Porosity* (pp. 17–28). 10.1007/978-3-030-87462-9_3

Bagdassarov, N. (2021). Density and Porosity. In Fundamentals of Rock Physics (pp. 28–65). Cambridge University Press. 10.1017/9781108380713.003

Bashir, A., Ali, M., Patil, S., Aljawad, M. S., Mahmoud, M., Al-Shehri, D., Hoteit, H., & Kamal, M. S. (2024). Comprehensive review of CO2 geological storage: Exploring principles, mechanisms, and prospects. *Earth-Science Reviews*, *249*, 104672. 10.1016/j.earscirev.2023.104672

Bui, M., Adjiman, C. S., Bardow, A., Anthony, E. J., Boston, A., Brown, S., Fennell, P. S., Fuss, S., Galindo, A., Hackett, L. A., Hallett, J. P., Herzog, H. J., Jackson, G., Kemper, J., Krevor, S., Maitland, G. C., Matuszewski, M., Metcalfe, I. S., Petit, C., … Mac Dowell, N. (2018). Carbon capture and storage (CCS): the way forward. *Energy & Environmental Science*, *11*(5), 1062–1176. 10.1039/C7EE02342A

Burtonshaw, J. E. J., Paluszny, A., Thomas, R. N., & Zimmerman, R. W. (2022, June 26). The Influence of Hydraulic Fluid Properties on Induced Seismicity During Underground Hydrogen Storage. *All Days*. 10.56952/ARMA-2022-0614

Cachola, C. da S., Ciotta, M., Azevedo dos Santos, A., & Peyerl, D. (2023). Deploying of the carbon capture technologies for CO2 emission mitigation in the industrial sectors. *Carbon Capture Science & Technology*, *7*, 100102. 10.1016/j.ccst.2023.100102

Cao, C., Liu, H., Hou, Z., Mehmood, F., Liao, J., & Feng, W. (2020). A Review of CO2 Storage in View of Safety and Cost-Effectiveness. *Energies*, *13*(3), 600. 10.3390/en13030600

Chabab, S., Théveneau, P., Coquelet, C., Corvisier, J., & Paricaud, P. (2020). Measurements and predictive models of high-pressure H2 solubility in brine (H2O+NaCl) for underground hydrogen storage application. *International Journal of Hydrogen Energy*, *45*(56), 32206–32220. 10.1016/j.ijhydene.2020.08.192

Chalbaud, C., Robin, M., Lombard, J.-M., Martin, F., Egermann, P., & Bertin, H. (2009). Interfacial tension measurements and wettability evaluation for geological CO2 storage. *Advances in Water Resources*, *32*(1), 98–109. 10.1016/j.advwatres.2008.10.012

Chang, Q., Dempsey, D., Zhang, L., Zhao, Y., & Huang, L. (2024). Molecular dynamics insights into gas-water interfacial tension: Optimizing hydrogen storage in subsurface conditions. *International Journal of Hydrogen Energy*, *64*, 896–905. 10.1016/j.ijhydene.2024.03.341

Chen, M., Zhang, Y., Liu, S., Zhao, C., Dong, S., & Song, Y. (2023). CO2 transport and carbonate precipitation in the coupled diffusion-reaction process during CO2 storage. *Fuel*, *334*, 126805. 10.1016/j.fuel.2022.126805

Cheng, Y., Liu, W., Xu, T., Zhang, Y., Zhang, X., Xing, Y., Feng, B., & Xia, Y. (2023). Seismicity induced by geological CO2 storage: A review. *Earth-Science Reviews*, *239*, 104369. 10.1016/j.earscirev.2023.104369

Ding, S., Xi, Y., Jiang, H., & Liu, G. (2018). CO2 storage capacity estimation in oil reservoirs by solubility and mineral trapping. *Applied Geochemistry*, *89*, 121–128. 10.1016/j.apgeochem.2017.12.002

Farokhpoor, R., Bjørkvik, B. J. A., Lindeberg, E., & Torsæter, O. (2013). Wettability behaviour of CO2 at storage conditions. *International Journal of Greenhouse Gas Control*, *12*, 18–25. 10.1016/j.ijggc.2012.11.003

Fatah, A., Amao, A., Abu-Mahfouz, I. S., & Al-Yaseri, A. (2024). Geochemical Reactions of High Total Organic Carbon Oil Shale during CO 2 Treatment Relevant to Subsurface Carbon Storage. *Energy & Fuels*, *38*(2), 1161–1172. 10.1021/acs.energyfuels.3c03958

Global CCS Institute. (2023). *Global Status of CCS Report 2023*. Retrieved from https://status23.globalccsinstitute.com/new-facilities/

Hassanpouryouzband, A., Joonaki, E., Edlmann, K., & Haszeldine, R. S. (2021). Offshore Geological Storage of Hydrogen: Is This Our Best Option to Achieve Net-Zero? *ACS Energy Letters*, *6*(6), 2181–2186. 10.1021/acsenergylett.1c00845

Heinemann, N., Booth, M. G., Haszeldine, R. S., Wilkinson, M., Scafidi, J., & Edlmann, K. (2018). Hydrogen storage in porous geological formations – onshore play opportunities in the midland valley (Scotland, UK). *International Journal of Hydrogen Energy*, *43*(45), 20861–20874. 10.1016/j.ijhydene.2018.09.149

Higgs, S., Da Wang, Y., Sun, C., Ennis-King, J., Jackson, S. J., Armstrong, R. T., & Mostaghimi, P. (2022). In-situ hydrogen wettability characterisation for underground hydrogen storage. *International Journal of Hydrogen Energy*, *47*(26), 13062–13075. 10.1016/j.ijhydene.2022.02.022

Hu, Q., Wang, Q., Zhang, T., Zhao, C., Iltaf, K. H., Liu, S., & Fukatsu, Y. (2023). Petrophysical properties of representative geological rocks encountered in carbon storage and utilization. *Energy Reports*, *9*, 3661–3682. 10.1016/j.egyr.2023.02.020

IEA. (2024). *Energy Technology Perspectives, Scenarios and Strategies to 2050.* Retrieved from https://www.iea.org/reports/energy-technology-perspectives-2020

Iordache, I., Schitea, D., Gheorghe, A. V., & Iordache, M. (2014). Hydrogen underground storage in Romania, potential directions of development, stakeholders and general aspects. *International Journal of Hydrogen Energy*, *39*(21), 11071–11081. 10.1016/j.ijhydene.2014.05.067

Janjua, S. Y., & Khan, M. R. (2023). Environmental implications of offshore oil and gas decommissioning options: an eco-efficiency assessment approach. *Environment, Development and Sustainability*, *25*(11), 12915–12944. 10.1007/s10668-022-02595-x

Jeon, J., & Kim, S. J. (2020). Recent Progress in Hydrogen Flammability Prediction for the Safe Energy Systems. *Energies*, *13*(23), 6263. 10.3390/en13236263

Khudaida, K. J., & Das, D. B. (2020). A Numerical Analysis of the Effects of Supercritical CO2 Injection on CO2 Storage Capacities of Geological Formations. *Clean Technologies*, *2*(3), 333–364. 10.3390/cleantechnol2030021

Li, Q., & Liu, G. (2016). Risk Assessment of the Geological Storage of CO2: A Review. In Geologic Carbon Sequestration (pp. 249–284). Cham: Springer International Publishing. 10.1007/978-3-319-27019-7_13

Liang, Y., Tsuji, S., Jia, J., Tsuji, T., & Matsuoka, T. (2017). Modeling CO 2 –Water–Mineral Wettability and Mineralization for Carbon Geosequestration. *Accounts of Chemical Research*, *50*(7), 1530–1540. 10.1021/acs.accounts.7b00049

Liu, J., Wang, S., Javadpour, F., Feng, Q., & Cha, L. (2022). Hydrogen Diffusion in Clay Slit: Implications for the Geological Storage. *Energy & Fuels*, *36*(14), 7651–7660. 10.1021/acs.energyfuels.2c01189

Liu, Q., Zhu, D., Jin, Z., Tian, H., Zhou, B., Jiang, P., Meng, Q., Wu, X., Xu, H., Hu, T., & Zhu, H. (2023). Carbon capture and storage for long-term and safe sealing with constrained natural CO2 analogs. *Renewable and Sustainable Energy Reviews*, *171*, 113000. 10.1016/j.rser.2022.113000

Loria, P., & Bright, M. B. H. (2021). Lessons captured from 50 years of CCS projects. *The Electricity Journal*, *34*(7), 106998. 10.1016/j.tej.2021.106998

Lysyy, M., Fernø, M., & Ersland, G. (2021). Seasonal hydrogen storage in a depleted oil and gas field. *International Journal of Hydrogen Energy*, *46*(49), 25160–25174. 10.1016/j.ijhydene.2021.05.030

Matos, C. R., Carneiro, J. F., & Silva, P. P. (2019). Overview of Large-Scale Underground Energy Storage Technologies for Integration of Renewable Energies and Criteria for Reservoir Identification. *Journal of Energy Storage*, *21*, 241–258. 10.1016/j.est.2018.11.023

Matter, J. M., Stute, M., Snæbjörnsdottir, S. Ó., Oelkers, E. H., Gislason, S. R., Aradottir, E. S., Sigfusson, B., Gunnarsson, I., Sigurdardottir, H., Gunnlaugsson, E., Axelsson, G., Alfredsson, H. A., Wolff-Boenisch, D., Mesfin, K., Taya, D. F. de la R., Hall, J., Dideriksen, K., & Broecker, W. S. (2016). Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions. *Science*, *352*(6291), 1312–1314. 10.1126/science.aad8132

Mendes, C. (2022). O que é uma revisão narrativa de literatura: exemplos e considerações da metodologia.

Metz, B., Davidson, O., de Coninck, H., Loos, M., & Meyer, L. (2005). *IPCC Special Report on Carbon dioxide Capture and Storage*.

Mito, S., & Xue, Z. (2011). Post-Injection monitoring of stored CO2 at the Nagaoka pilot site: 5 years time-lapse well logging results. *Energy Procedia*, *4*, 3284–3289. 10.1016/j.egypro.2011.02.248

Muhammed, N. S., Haq, M. B., Al Shehri, D. A., Al-Ahmed, A., Rahman, M. M., Zaman, E., & Iglauer, S. (2023). Hydrogen storage in depleted gas reservoirs: A comprehensive review. *Fuel*, *337*, 127032. 10.1016/j.fuel.2022.127032

Nielsen, L. C., Bourg, I. C., & Sposito, G. (2012). Predicting CO2–water interfacial tension under pressure and temperature conditions of geologic CO2 storage. *Geochimica et Cosmochimica Acta*, *81*, 28–38. 10.1016/j.gca.2011.12.018

Olabi, A. G., Bahri, A. saleh, Abdelghafar, A. A., Baroutaji, A., Sayed, E. T., Alami, A. H., Rezk, H., & Abdelkareem, M. A. (2021). Large-vscale hydrogen production and storage technologies: Current status and future directions. *International Journal of Hydrogen Energy*, *46*(45), 23498–23528. 10.1016/j.ijhydene.2020.10.110

Omrani, S., Ghasemi, M., Mahmoodpour, S., Shafiei, A., & Rostami, B. (2022). Insights from molecular dynamics on CO2 diffusion coefficient in saline water over a wide range of temperatures, pressures, and salinity: CO2 geological storage implications. *Journal of Molecular Liquids*, *345*, 117868. 10.1016/j.molliq.2021.117868

Osman, A. I., Mehta, N., Elgarahy, A. M., Hefny, M., Al-Hinai, A., Al-Muhtaseb, A. H., & Rooney, D. W. (2022). Hydrogen production, storage, utilisation and environmental impacts: a review. *Environmental Chemistry Letters*, *20*(1), 153–188. 10.1007/s10311-021-01322-8

Osmundsen, P., & Tveterås, R. (2003). Decommissioning of petroleum installations—major policy issues. *Energy Policy*, *31*(15), 1579–1588. 10.1016/S0301-4215(02)00224-0

Pan, B., Yin, X., Ju, Y., & Iglauer, S. (2021). Underground hydrogen storage: Influencing parameters and future outlook. *Advances in Colloid and Interface Science*, *294*, 102473. 10.1016/j.cis.2021.102473

Perera, M. S. A. (2023). A review of underground hydrogen storage in depleted gas reservoirs: Insights into various rock-fluid interaction mechanisms and their impact on the process integrity. *Fuel*, *334*, 126677. 10.1016/j.fuel.2022.126677

Priolo, E., Romanelli, M., Plasencia Linares, M. P., Garbin, M., Peruzza, L., Romano, M. A., Marotta, P., Bernardi, P., Moratto, L., Zuliani, D., & Fabris, P. (2015). Seismic Monitoring of an Underground Natural Gas Storage Facility: The Collalto Seismic Network. *Seismological Research Letters*, *86*(1), 109–123. 10.1785/0220140087

Safari, A., Zeng, L., Nguele, R., Sugai, Y., & Sarmadivaleh, M. (2022). Review on using the depleted gas reservoirs for the underground H2 storage: A case study in Niigata prefecture, Japan. *International Journal of Hydrogen Energy*. 10.1016/j.ijhydene.2022.12.108

Sapiie, B., Danio, H., Priyono, A., Asikin, A. R., Widarto, D. S., Widianto, E., & Tsuji, T. (2015). Geological characteristic and fault stability of the Gundih CCS pilot project at central Java, Indonesia. *Proceedings of the 12th SEGJ International Symposium, Tokyo, Japan, 18-20 November 2015*, 110–113. 10.1190/segj122015-029

Shukla, R., Ranjith, P., Haque, A., & Choi, X. (2010). A review of studies on CO2 sequestration and caprock integrity. *Fuel*, *89*(10), 2651–2664. 10.1016/j.fuel.2010.05.012

Sorai, M., Lei, X., Nishi, Y., Ishido, T., & Nakao, S. (2022). CO2 Geological Storage. In Handbook of Climate Change Mitigation and Adaptation (pp. 1531–1584). Cham: Springer International Publishing. 10.1007/978-3-030-72579-2_85

SpringerMaterials. (2024a). *Carbon Dioxide*. Retrieved from https://materials.springer.com/substanceprofile/docs/smsid_opysrkklmfnjkqqv

SpringerMaterials. (2024b). *Dihydrogen*. Retrieved from https://materials.springer.com/substanceprofile/docs/smsid_izescefequkgdfgz

Stephenson, M. H., Ringrose, P., Geiger, S., Bridden, M., & Schofield, D. (2019). Geoscience and decarbonization: current status and future directions. *Petroleum Geoscience*, *25*(4), 501–508. 10.1144/petgeo2019-084

Tajnik, T., Bogataj, L. K., Jurač, E., Lasnik, C. R., Likar, J., & Debelak, B. (2013). Investigation of adsorption properties of geological materials for CO 2 storage. *International Journal of Energy Research*, *37*(8), 952–958. 10.1002/er.2901

Tarkowski, R. (2017). Perspectives of using the geological subsurface for hydrogen storage in Poland. *International Journal of Hydrogen Energy*, *42*(1), 347–355. 10.1016/j.ijhydene.2016.10.136

Tarkowski, R. (2019). Underground hydrogen storage: Characteristics and prospects. *Renewable and Sustainable Energy Reviews and Sustainable Energy Reviews*, *105*, 86–94.

Tarkowski, R., Uliasz-Misiak, B., & Tarkowski, P. (2021). Storage of hydrogen, natural gas, and carbon dioxide – Geological and legal conditions. *International Journal of Hydrogen Energy*, *46*(38), 20010–20022. 10.1016/j.ijhydene.2021.03.131

Thomas, K. M. (2007). Hydrogen adsorption and storage on porous materials☆. *Catalysis Today*, *120*(3-4), 389–398. 10.1016/j.cattod.2006.09.015

Tilford, N. R., Cannon, R. P., & Saleem, Z. A. (1983). Tectonic stability aspects of high-level radioactive waste repository siting and licensing. *Waste Management Conference*, 3.

Tomić, L., Karović-Maričić, V., Danilović, D., & Crnogorac, M. (2018). Criteria for CO2 storage in geological formations. *Podzemni Radovi*, *32*. 10.5937/PodRad1832061T

Uliasz-Misiak, B., Lewandowska-Śmierzchalska, J., & Matuła, R. (2021). Selection of Underground Hydrogen Storage Risk Assessment Techniques. *Energies*, *14*(23), 8049. 10.3390/en14238049

Vargaftik, N. B. (1975). *Handbook of physical properties of liquids and gases - pure substances and mixtures.*

Verga, F. (2018). What's Conventional and What's Special in a Reservoir Study for Underground Gas Storage. *Energies*, *11*(5), 1245. 10.3390/en11051245

Wang, J., Samara, H., Ko, V., Rodgers, D., Ryan, D., & Jaeger, P. (2023). Analysis of the Impact of CO 2 Adsorption on Rock Wettability for Geological Storage of CO 2. *Energy & Fuels*, *37*(18), 14046–14052. 10.1021/acs.energyfuels.3c00909

Wang, T., Yang, C., Ma, H., Daemen, J. J. K., & Wu, H. (2015). Safety evaluation of gas storage caverns located close to a tectonic fault. *Journal of Natural Gas Science and Engineering*, *23*, 281–293. 10.1016/j.jngse.2015.02.005

Wei, B., Wang, B., Li, X., Aishan, M., & Ju, Y. (2023). CO2 storage in depleted oil and gas reservoirs: A review. *Advances in Geo-Energy Research*, *9*(2), 76–93. 10.46690/ager.2023.08.02

Witkowski, A., Rusin, A., Majkut, M., & Stolecka, K. (2017). Comprehensive analysis of hydrogen compression and pipeline transportation from thermodynamics and safety aspects. *Energy*, *141*, 2508–2518. 10.1016/j.energy.2017.05.141

Yang, F., Wang, T., Deng, X., Dang, J., Huang, Z., Hu, S., Li, Y., & Ouyang, M. (2021). Review on hydrogen safety issues: Incident statistics, hydrogen diffusion, and detonation process. *International Journal of Hydrogen Energy*, *46*(61), 31467–31488. 10.1016/j.ijhydene.2021.07.005

Yang, N., Deng, J., Wang, C., Bai, Z., & Qu, J. (2024). High pressure hydrogen leakage diffusion: Research progress. *International Journal of Hydrogen Energy*, *50*, 1029–1046. 10.1016/j.ijhydene.2023.08.221

Zhang, C., & Wang, M. (2023). CO2/brine interfacial tension for geological CO2 storage: A systematic review. *Journal of Petroleum Science and Engineering*, *220*, 111154. 10.1016/j.petrol.2022.111154

Zhang, K., Jin, Z., Li, G., Liu, Q., & Tian, L. (2023). Gas adsorptions of geological carbon storage with enhanced gas recovery. *Separation and Purification Technology*, *311*, 123260. 10.1016/j.seppur.2023.123260

Zhang, S., & DePaolo, D. J. (2017). Rates of CO 2 Mineralization in Geological Carbon Storage. *Accounts of Chemical Research*, *50*(9), 2075–2084. 10.1021/acs.accounts.7b00334

Zhong, H., Wang, Z., Zhang, Y., Suo, S., Hong, Y., Wang, L., & Gan, Y. (2024). Gas storage in geological formations: A comparative review on carbon dioxide and hydrogen storage. *Materials Today Sustainability*, 100720. 10.1016/j.mtsust.2024.100720

Zhu, H., Ju, Y., Qi, Y., Huang, C., & Zhang, L. (2018). Impact of tectonism on pore type and pore structure evolution in organic-rich shale: Implications for gas storage and migration pathways in naturally deformed rocks. *Fuel*, *228*, 272–289. 10.1016/j.fuel.2018.04.137