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A Geological Screening Framework for Underground Green Hydrogen Storage in Libya: Basin-Scale Evaluation and Site Prioritization

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إطار عمل للفحص الجيولوجي لتخزين الهيدروجين الأخضر تحت الأرض في ليبيا: تقييم على مستوى الحوض وتحديد أولويات المواقع

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Abstract:
The global transition toward low-carbon energy systems has intensified the demand for large-scale, safe, and cost-effective hydrogen storage solutions to support renewable energy integration. Libya possesses significant solar and wind resources, along with extensive sedimentary basins; however, its potential for underground hydrogen storage (UHS) remains insufficiently explored. This study presents a comprehensive geological evaluation and comparative assessment of Libya's major sedimentary basins the Sirte, Ghadames, and Murzuq basins with a focus on depleted hydrocarbon reservoirs as the most feasible storage option. Salt caverns, widely regarded as optimal for hydrogen storage, are not viable in Libya due to the absence of sufficiently thick and laterally continuous salt formations. Instead, mature and over-mature fields particularly sandstone and carbonate formations offer a practical. These reservoirs exhibit favorable petrophysical properties, including porosity ranging from 15% to 30% and permeability exceeding 100 mD, along with effective regional caprocks such as evaporites and shale sequences. To support systematic site selection, a screening framework is applied that integrates reservoir quality, caprock integrity, structural stability, and infrastructure availability, enabling risk-informed ranking of candidate sites. Results indicate that the Sirte Basin represents the most suitable candidate for Phase 1 pilot implementation and commercial-scale deployment due to its abundance of mature and depleted reservoirs, large storage capacity, extensive infrastructure, and proximity to major export terminals. The Ghadames Basin emerges as a viable secondary option, while the Murzuq Basin remains a longer-term prospect. Overall, Libya demonstrates strong geological potential for UHS; however, further site-specific investigations are required to ensure long-term storage integrity and operational feasibility. Key priorities include infrastructure integrity assessments, targeted geochemical analyses, the development of a national regulatory framework, and the expansion of the UHSSI into a nationwide storage mapping tool.

Keywords: Green Hydrogen, Underground Storage, Geology, Libya, Energy Transition.

الملخص:
أدى التحول العالمي نحو أنظمة الطاقة منخفضة الكربون إلى زيادة الطلب على حلول تخزين الهيدروجين واسعة النطاق والآمنة والفعالة من حيث التكلفة لدعم دمج الطاقة المتجددة. تمتلك ليبيا موارد كبيرة من الطاقة الشمسية وطاقة الرياح، إلى جانب أحواض رسوبية واسعة؛ ومع ذلك، لا يزال استكشاف إمكاناتها لتخزين الهيدروجين تحت الأرض غير كافٍ. تقدم هذه الدراسة تقييمًا جيولوجيًا شاملًا ودراسة مقارنة للأحواض الرسوبية الرئيسية في ليبيا، وهي أحواض سرت وغدامس ومرزق، مع التركيز على خزانات الهيدروكربونات المستنفدة باعتبارها الخيار الأمثل للتخزين. لا تُعد الكهوف الملحية، التي يُنظر إليها على نطاق واسع على أنها مثالية لتخزين الهيدروجين، خيارًا عمليًا في ليبيا نظرًا لعدم وجود تكوينات ملحية سميكة ومتصلة جانبيًا بشكل كافٍ. في المقابل، توفر الخزانات في الحقول الناضجة والناضجة جدًا، والتي تتكزن من وحدات الحجر الرملي والحجر الجيري، بديلاً عمليًا وقابلاً للتوسع. تتميز هذه المكامن بخصائص بتروفيزيائية مواتية، بما في ذلك مسامية تتراوح بين 15% و30% ونفاذية تتجاوز 100 ملي دارسي، بالإضافة إلى طبقات عازلة إقليمية فعّالة مثل المتبخرات وتتابعات الطفلة. ولدعم اختيار المواقع بشكل منهجي، يُطبّق إطار عمل فرز يدمج جودة المكمن، وسلامة الطبقة العازلة، والاستقرار البنيوي، وتوافر البنية التحتية، مما يُتيح تصنيف المواقع المرشحة بناءً على تقييم المخاطر. تُشير النتائج إلى أن حوض سرت يُمثّل المرشح الأنسب لتنفيذ المرحلة الأولى تجريبياً ونشر المشروع على نطاق تجاري، وذلك بفضل وفرة المكامن الناضجة والمستنفدة فيه، وسعته التخزينية الكبيرة، وبنيته التحتية الواسعة، وقربه من موانئ التصدير الرئيسية. ويبرز حوض غدامس كخيار ثانوي قابل للتطبيق، بينما يبقى حوض مرزق خياراً طويل الأجل. بشكل عام، تُظهر ليبيا إمكانات جيولوجية قوية لأنظمة التخزين تحت الأرض؛ ومع ذلك، يلزم إجراء المزيد من الدراسات الخاصة بكل موقع لضمان سلامة التخزين على المدى الطويل وجدوى التشغيل. تشمل الأولويات الرئيسية تقييمات سلامة البنية التحتية، والتحليلات الجيوكيميائية المتخصصة، ووضع إطار تنظيمي وطني، وتوسيع نطاق نظام معلومات التخزين تحت الأرض ليصبح أداةً شاملةً لرسم خرائط التخزين على مستوى الدولة.

الكلمات المفتاحية: الهيدروجين الأخضر، التخزين تحت الأرض، الجيولوجيا، ليبيا، التحول الطاقي.

1. Introduction

The accelerating impacts of global climate change have intensified the transition toward sustainable and low-carbon energy systems, positioning hydrogen as a critical energy carrier for decarbonizing hard-to-abate sectors such as heavy industry and long-distance transportation. When produced and utilized through clean pathways, hydrogen emits only water as a byproduct, offering a promising route toward carbon-neutral energy systems [1]. Among the various production pathways, green hydrogen generated via water electrolysis powered by renewable energy sources such as solar and wind represents a near-zero-emission solution essential for achieving long-term net-zero targets [2,3].

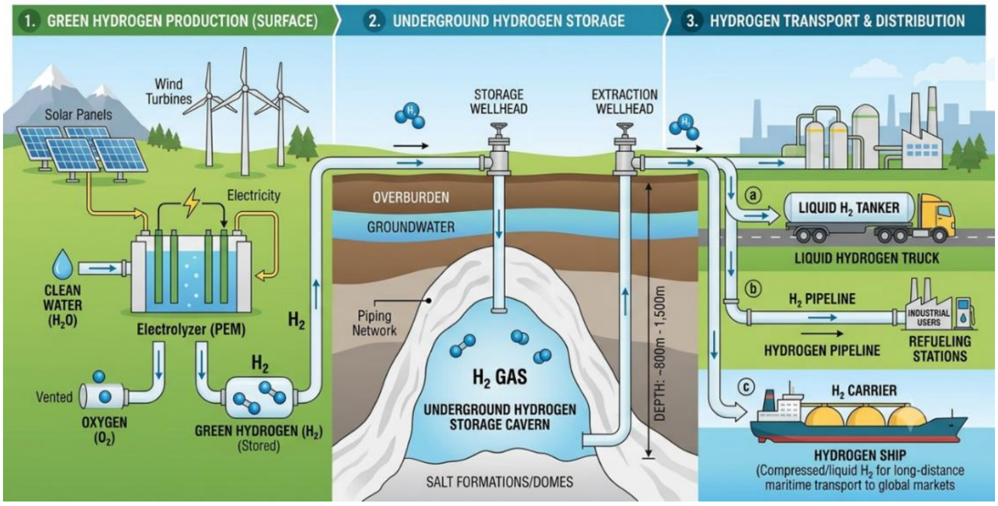

Figure 1: Green hydrogen supply chain.

Figure 1, illustrates the integrated green hydrogen supply chain, from renewable energy production to underground storage and final distribution. Green hydrogen is produced by water electrolysis using electricity generated from solar and wind energy. The hydrogen is then injected into suitable subsurface geological formations, such as salt caverns, for large-scale and long-term storage. When needed, it is recovered through production wells and transported via pipelines, liquid hydrogen tankers, or maritime carriers to industrial users and refueling stations. This integrated system enhances energy security, improves sustainable renewable energy integration, and supports the transition toward a low-carbon energy future.

Global hydrogen demand reached approximately 95 million tonnes (Mt) in 2022 and increased to nearly 100 Mt by 2024, driven largely by conventional applications such as petroleum refining and ammonia production. However, low-emission hydrogen currently accounts for less than 1% of total supply, highlighting a significant gap between climate ambitions and existing production capacity [4]. Bridging this gap requires not only scaling up green hydrogen production but also developing reliable storage and distribution infrastructure.

One of the primary challenges hindering large-scale hydrogen deployment is the difficulty of achieving efficient, safe, and cost-effective storage. Due to its low volumetric energy density, hydrogen requires compression, liquefaction, or alternative storage methods, each associated with technical and economic constraints [5]. Consequently, large-scale and long-duration storage solutions are essential to balance the intermittency of renewable energy sources and to ensure a stable and continuous energy supply. In this context, underground hydrogen storage (UHS) has emerged as a promising solution, enabling the storage of substantial hydrogen volumes in geological formations such as salt caverns, depleted oil and gas reservoirs, and deep saline aquifers.

In recent years, North Africa has attracted increasing attention as a strategic region for green hydrogen production, primarily due to its abundant renewable energy resources and favorable climatic conditions. Countries such as Egypt, Morocco, and Algeria have already initiated large-scale projects aimed at producing and exporting green hydrogen, particularly to European markets. These developments underscore the region's growing importance in the global hydrogen economy [6].

Libya, in particular, possesses significant potential for green hydrogen development, supported by its exceptional solar energy capacity and extensive sedimentary basins containing thick sequences of sandstone, carbonate, shale, and evaporite rocks, as well as mature and overmature hydrocarbon fields [7,8]. These geological settings provide favorable conditions for underground hydrogen storage. Despite this potential, comprehensive and systematic geological evaluations of suitable storage sites in Libya remain limited. Therefore, this study aims to address this gap by developing a geological evaluation and site-screening framework, focusing on the petrophysical and structural characteristics of key subsurface formations to assess their suitability for hydrogen storage and to identify priority locations for future development.

1.1. Problem Statement

Despite Libya's abundant solar resources and the presence of extensive sedimentary basins with mature and over mature hydrocarbon fields. A significant research gap persists in the systematic geological evaluation of its subsurface formations for large-scale underground hydrogen storage (UHS). Existing global research on UHS has predominantly focused on geological settings in Europe, North America, and parts of Asia, with very limited attention devoted to North African contexts in general and Libya in particular (Figure 2) [9].

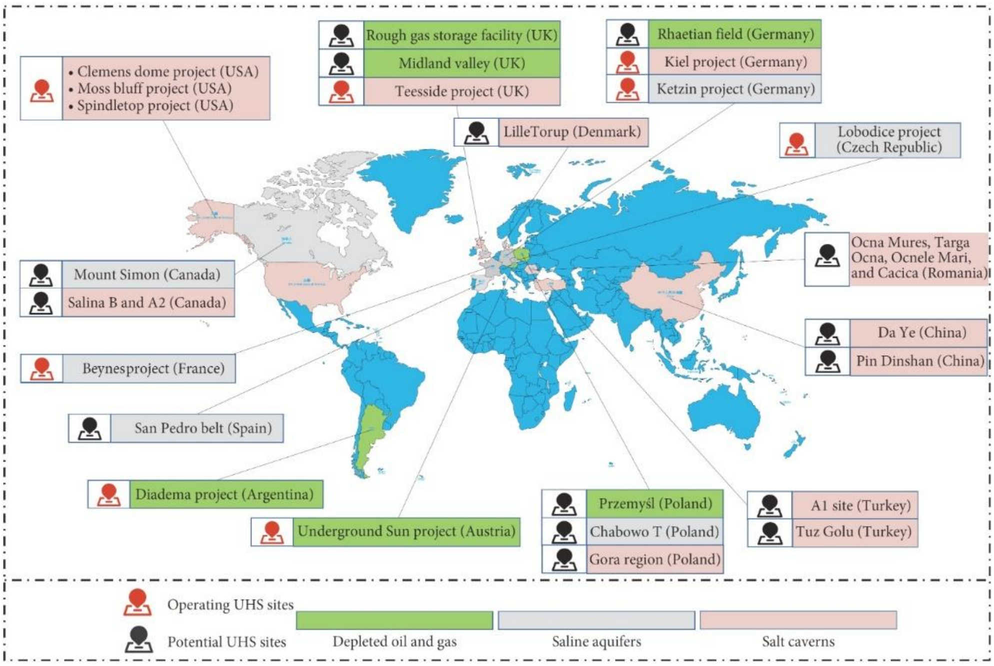

Figure 2: A schematic diagram of existing and potential UHS sites [9].

Recent bibliometric analyses confirm that Libya's contribution to green hydrogen research remains modest overall, and studies specifically addressing underground storage are scarce. Critical knowledge gaps include detailed reservoir characterization, caprock sealing integrity, potential geochemical interactions between hydrogen and rock formations, and the geomechanical response of these formations under repeated hydrogen injection-withdrawal cycles. These uncertainties hinder accurate assessment of storage capacity, long-term safety, and operational efficiency. Addressing them is essential to determine the technical feasibility and economic viability of geological hydrogen storage in Libya, thereby enabling the country to leverage its renewable energy potential and support both domestic decarbonization and possible hydrogen exports. Therefore, a structured geological evaluation framework is essential to unlock Libya's potential for underground hydrogen storage.

1.2. Research Objectives

This study aims to establish a comprehensive geological framework for green hydrogen storage in Libya. The specific objectives are:

1. To identify and map potential geological storage sites within Libya's major sedimentary basins, focusing on salt formations, depleted hydrocarbon reservoirs, and deep saline aquifers.
2. To characterize the petrophysical, sealing capacity and structural properties of candidate reservoir formations, including porosity, permeability, and heterogeneity.
3. To provide a preliminary technical feasibility assessment of underground hydrogen storage in selected Libyan sites, considering geomechanical stability, potential leakage risks, and operational constraints.

The findings are expected to offer actionable insights for policymakers and energy developers, contributing to the development of a sustainable hydrogen economy in Libya and supporting the country's broader transition to a low-carbon energy system.

2. Underground hydrogen storage (UHS)

As previously discussed, one of the major challenges facing green hydrogen as a promising clean energy carrier is efficient and sustainable storage. In the early stages of hydrogen utilization, storage relied primarily on batteries and other electrochemical systems. However, these methods present several limitations, including environmental, geopolitical, and technical issues [1], [10,12]. An alternative method that could allow storage of high volumes of hydrogen to be used at need is underground storage of gaseous hydrogen [13,14].

Underground hydrogen storage (UHS) is considered analogous to underground natural gas storage operations that have been successfully implemented for over a century in salt caverns, depleted reservoirs, and aquifers. However, there is minimal operational experience with hydrogen storage in these systems. A typical UHS site aims to provide storage potential to balance seasonal supply and demand fluctuations and meet peak demand to stabilize the power grid. UHS can utilize naturally occurring porous media or engineered structures in the subsurface for viable large-scale and seasonal energy storage capability [15].

Underground Hydrogen Storage (UHS) provides several key advantages over surface storage systems. First, it offers enhanced safety and security, as subsurface facilities are less exposed to external hazards such as fires, attacks, and extreme weather events, while also reducing the risk of hydrogen leakage. Second, UHS is more space-efficient, enabling the storage of large hydrogen volumes within a limited surface footprint and minimizing the need for extensive above-ground infrastructure. Third, it presents economic benefits through lower construction, operation, and maintenance costs, along with the ability to store hydrogen over long periods with minimal losses. Finally, the widespread availability of suitable geological formations such as depleted reservoirs, salt caverns, and aquifers supports the global feasibility and flexibility of UHS deployment [16-19].

The underground hydrogen storage (UHS) options generally fall into three main geological categories (Figure 3):

1. Depleted reservoirs in the Oil and Gas Fields
2. Deep saline aquifers hosted in porous geological formations
3. Storage in salt and lined rock caverns [20,21].

As shown in Table 1, all three primary geological options for underground hydrogen storage salt caverns, deep saline aquifers, and depleted hydrocarbon reservoirs have demonstrated technical feasibility and varying degrees of operational success in pilot or commercial-scale projects worldwide. Salt caverns excel in providing high-purity hydrogen storage with rapid cycling capability and excellent mechanical integrity due to the self-healing properties of salt. Deep saline aquifers offer potentially large storage volumes but require extensive upfront characterization and carry higher uncertainties regarding containment and fluid-rock interactions. Depleted hydrocarbon reservoirs, while introducing challenges related to residual fluids and potential biogeochemical reactions, benefit from proven trap integrity, detailed pre-existing geological data, and the ability to repurpose legacy infrastructure.

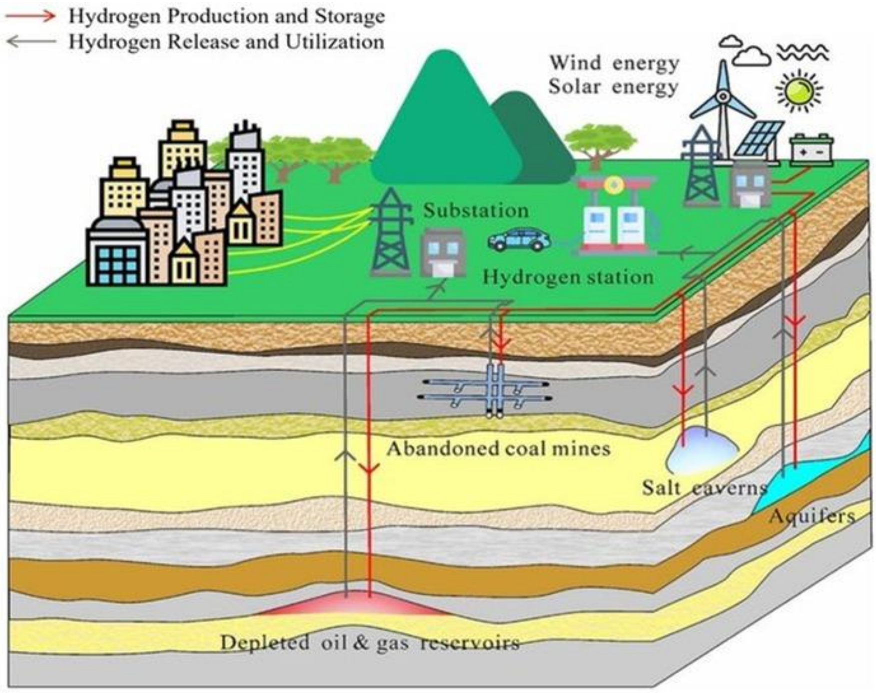

Figure 3. Schematic representation of the main UHS types [22,23].

Table 1. Comparative Overview of Main Underground Hydrogen Storage [15], [24].

		Underground hydrogen storage (UHS)		
		Depleted Oil and Gas Fields	**Saline Deep Aquifer**	**Salt Cavernous**
General	Advantages	Abundant	Abundant	Little Cushion Gas needed
	Disadvantages	Large Cushion Gas requirement	Need Exploration and high Cushion Gas needed	High Cost
Geological Characteristics	Advantages	Well understand geology	Well understand geology	Proven H_2 storage
	Disadvantages	Potential viscous fingering and interaction with residual HC	Lack of existing geological characteristics	Salt geochemically unstable
Infrastructure	Advantages	Available	Tailored infrastructure build-out	Only 1 well needed
	Disadvantages	Containment risk	Need infrastructure and drill wells	Require pipelines
Cost		Low (1.43$/kg)	Low (1.29$/kg)	Moderate (1.61$/kg)
Storage Capacity		Moderate to High	High	Low to Moderate

Depleted oil and gas reservoirs are considered prime candidates for hydrogen storage due to their well-defined trap structures, adequate porosity, and reliable sealing capacity (Fig. 4). These reservoirs, typically composed of sandstone and carbonate lithologies, have been extensively utilized for hydrocarbon storage, providing a strong foundation for their application in hydrogen storage [25]. The presence of competent caprocks acts as an effective barrier against gas leakage, while the porous reservoir formations offer substantial storage capacity [26,27]. Field-scale studies have demonstrated recovery efficiencies of up to 87%, particularly when residual gas is used as cushion gas, with notable potential observed in formations such as the Norne Field (Norway) and the Bakken Formation (USA) [28].

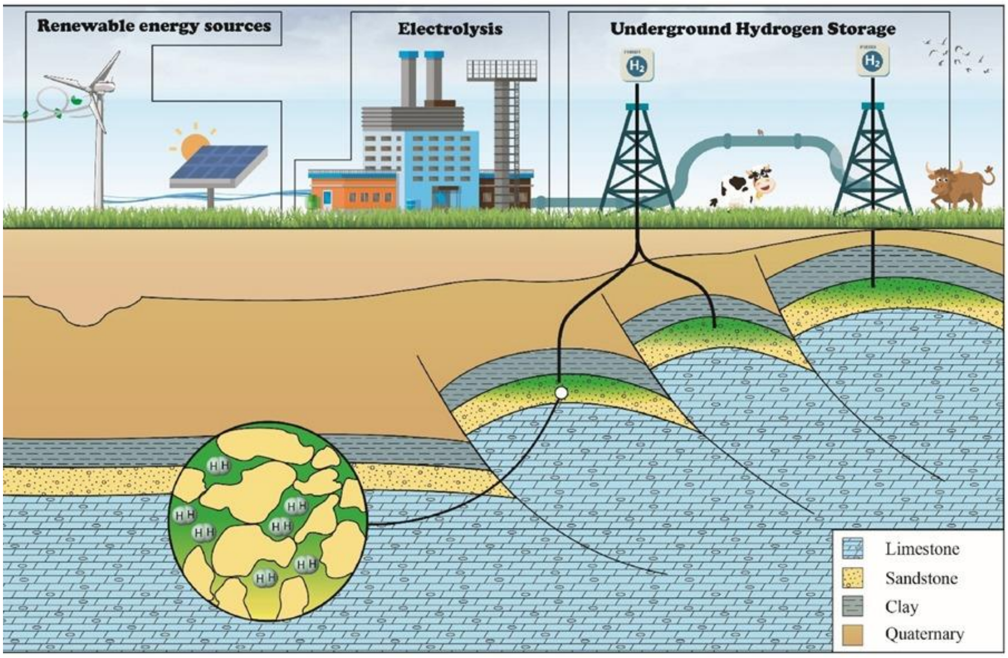

Figure 4: A schematic representation production and storage in the Depleted reservoirs [14].

Sandstone reservoirs are generally preferred for UHS due to their homogeneous intergranular porosity, moderate to high permeability, predictable flow behavior, and minimal geochemical reactivity with hydrogen. In contrast, carbonate reservoirs feature highly heterogeneous pore systems dominated by fractures, vugs, and dissolution features, resulting in variable permeability, complex fluid flow, greater leakage risk through fractures, and higher potential for geochemical or microbial interactions. While carbonates may offer substantial storage capacity, they require detailed site-specific geological, geomechanical, and geochemical evaluation, making sandstones the more reliable and lower-risk option for efficient hydrogen injection, storage, and recovery [29].

In the Libyan context, this study focuses primarily on depleted oil and gas reservoirs. These formations represent the most immediately viable and economically attractive option, given the country's extensive portfolio of mature and over-mature hydrocarbon fields. In contrast, salt caverns are not readily available in Libya, as the country lacks sufficiently thick, pure halite-dominated salt domes or bedded salt sequences suitable for solution mining and large-scale cavern construction. Similarly, storage in deep saline (brine) aquifers is deprioritized due to the limited existing infrastructure, sparse site-specific geological and petrophysical data, and the substantial additional investment required for exploration, well drilling, and surface facilities. Repurposing depleted reservoirs therefore offers a strategic pathway that leverages Libya's long-established petroleum systems, proven cap-rock seals, and existing pipeline and processing networks, thereby minimizing capital expenditure and deployment timelines while supporting the transition toward a green hydrogen economy.

3. Methodology: Technical Evaluation for Underground Hydrogen Storage (UHS) Site Selection

The selection of suitable sites for Underground Hydrogen Storage (UHS) demands a comprehensive and multidisciplinary workflow integrating structural geology, geomechanics, and reservoir engineering [25]. This methodology aims to pinpoint subsurface formations that offer a balance of high containment security and superior operational efficiency. The technical evaluation is structured into two core analytical stages: assessing the structural framework and characterizing the reservoir's petrophysical properties. The final stage integrates these parameters into a unified viability ranking system.

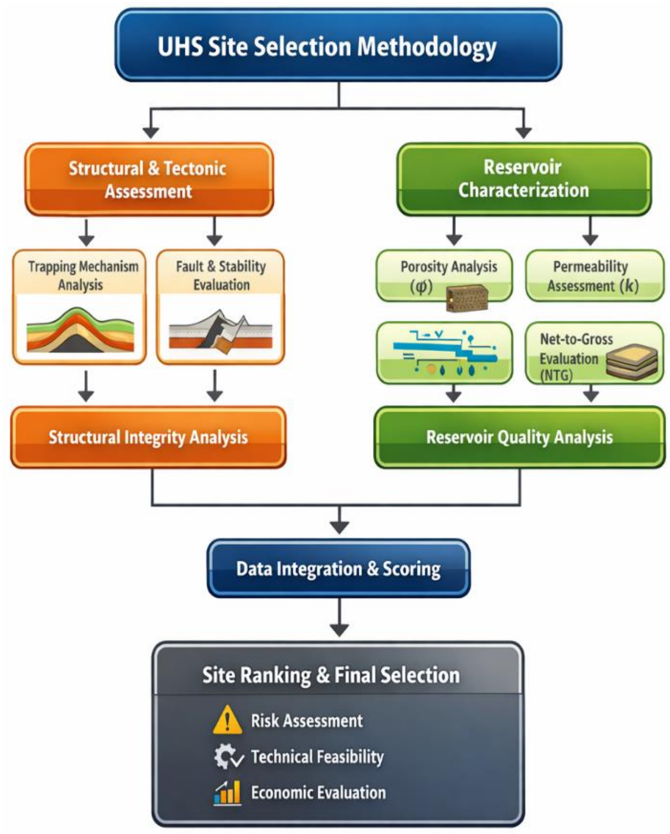

Figure 5: The UHS site selection methodology.

3.1 Structural and Tectonic Framework Assessment

The first phase focuses on a thorough examination of the regional and local tectonic setting to ensure secure, long-term hydrogen containment.

- Trapping Mechanism Identification: Candidate sites are assessed according to their trapping styles. Preferred structures include domal anticlines, fault-bounded traps, and stratigraphic traps. These configurations must provide an effective three-dimensional seal capable of preventing both vertical and lateral migration of hydrogen.
- Structural Stability and Fault Analysis: Detailed mapping and evaluation of fault networks are performed to quantify the risk of leakage. Geologically stable structures with minimal fault-related risks are prioritized. Particular attention is given to mitigating geomechanical hazards, such as induced seismicity or seal breach, which could arise from repeated high-pressure injection and withdrawal cycles.

3.2 Reservoir Quality and Petrophysical Characterization

Once structural integrity is verified, the storage capacity and deliverability of the reservoir are evaluated using key petrophysical properties obtained from well logs and core analyses.

- Storage Capacity (Porosity): Effective porosity (ϕ phi) serves as the main parameter for estimating the available pore volume for hydrogen storage. Formations with high porosity are preferred to achieve greater storage capacity and higher energy density.
- Flow Dynamics (Permeability): Permeability (k) is assessed to determine the reservoir's ability to support efficient fluid movement. Given the need for rapid injection and withdrawal rates in green hydrogen applications, high-permeability intervals are strongly favored to ensure excellent injectivity and deliverability.
- Reservoir Heterogeneity (Net-to-Gross Ratio): The Net-to-Gross (NTG) ratio is used to evaluate reservoir continuity and homogeneity. A high NTG value indicates a more uniform reservoir, which promotes predictable hydrogen distribution and improved recovery efficiency (RE). Reservoirs with low NTG ratios may exhibit compartmentalization, leading to inefficient hydrogen distribution.

3.3 Integrated Viability Matrix

The final step integrates structural, geomechanical, and petrophysical data into a comprehensive viability matrix. This synthesis enables the ranking and prioritization of potential UHS sites according to technical feasibility, safety, and performance criteria, ensuring that only formations meeting the highest standards for large-scale hydrogen storage are selected [21], [30].

4. Result: The Potential for Underground Green Hydrogen Storage in Libya

Libya possesses substantial potential for underground green hydrogen storage (UHS), particularly through the repurposing of its numerous sedimentary basins; Sirte, Ghadames and Murzuq basins contain many mature and depleted oil and gas fields (Figure 6). Globally, subsurface hydrogen storage has been demonstrated in various geological formations, including salt caverns, deep saline aquifers, and depleted hydrocarbon fields. Among these, depleted hydrocarbon reservoirs offer distinct advantages in regions with mature petroleum systems, as they benefit from proven containment history, extensive geological characterization, and existing surface infrastructure.

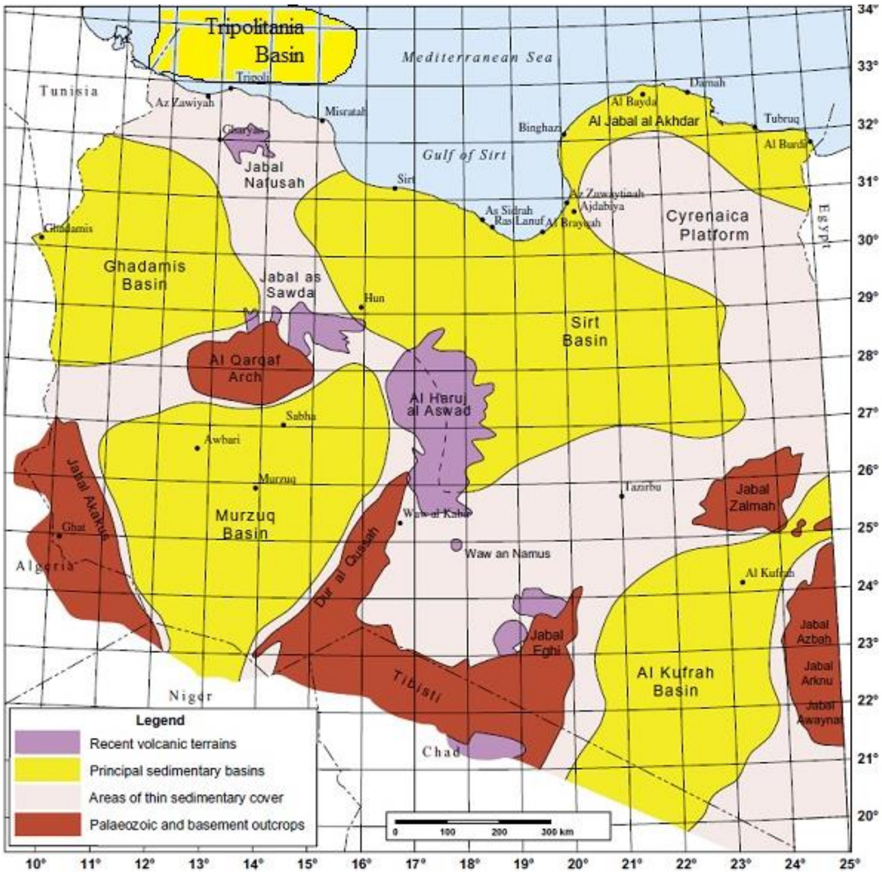

Figure 6: The Principal Libyan Basins [8].

In Libya, a significant proportion of oil and gas fields have reached a mature or over-mature stage of production, making them prime candidates for conversion into hydrogen storage facilities. These field reservoirs are predominantly hosted in sandstone and carbonate formations that display favorable petrophysical properties, notably high porosity (typically 15–30%) and permeability (often exceeding 100 mD in reservoir intervals). Such characteristics enable efficient injectivity and deliverability during cyclic hydrogen injection and withdrawal operations [8], [31,32]. Furthermore, the structural and stratigraphic styles of many Libyan hydrocarbon traps commonly faults, anticlines, stratigraphic pinchouts, carbonate build-up and combination traps provides well-defined, laterally continuous storage volumes. Examples of Libyan traps:

- Faults: Sarir “C” Main – Jalu - El Feel
- Anticlines: Awjilah-Nafurah - Dahra and Hofra - El Shararah – Hamra - Sabah
- Pinchouts: Messlah – Al Wafa
- Carbonate build-up: Intisar “A and D” - Zelten (Nasser)

Equally critical is the presence of robust sealing formations. Competent cap rocks, frequently consisting of thick evaporitic sequences (e.g., anhydrite and halite layers of the lower Eocene Hun evaporite succession in Sirte Basin) or regionally extensive low-permeability shale units (such as those within the Silurian Tanezzuft and Awaynat Wanin formations in Ghadames and Murzuq basins or Sirte

Shale, Etel, Rachmat, Harash, Kheir and Khalifa Shale formations in Sirte Basin), act as effective barriers to vertical fluid migration. These seals have successfully retained hydrocarbons for millions of years, suggesting strong potential for long-term hydrogen containment, subject to detailed geochemical and geomechanical validation [31].

Furthermore, Libya's sedimentary basins are generally characterized by a high degree of tectonic stability, which is a critical factor in assessing the long-term security of underground hydrogen storage. This stability is supported by the very low seismic activity recorded across most of the country, indicating a relatively inactive tectonic regime compared to more seismically active regions. In addition, the majority of mapped faults within these basins are considered geologically inactive or immobile, having undergone little to no recent displacement. Such conditions significantly reduce the risk of fault reactivation during hydrogen injection and withdrawal operations [32]. The absence of observable hydrocarbon seepage to the surface further suggests that these fault systems and overlying cap rocks have maintained their sealing capacity over geological timescales. Consequently, the combination of tectonic quiescence, fault stability, and effective natural sealing mechanisms enhances the integrity and reliability of Libyan subsurface formations as secure and long-term repositories for green hydrogen storage.

The economic and operational feasibility of UHS in Libya is further strengthened by the country's well-developed petroleum infrastructure. Existing wellbores, gathering systems, processing facilities, and extensive pipeline networks can be partially repurposed, significantly reducing capital expenditure and accelerating project deployment compared to greenfield storage developments. Moreover, Libya's strategic geographic location, abundant renewable energy resources (particularly solar and wind), and proximity to European hydrogen markets position the country as a potentially important player in the emerging global hydrogen economy [33].

Successful implementation of underground hydrogen storage in depleted Libyan fields will, however, require comprehensive site-specific assessments. These should include detailed reservoir characterization, hydrogen-rock-fluid interaction studies, geomechanical integrity analysis under cyclic loading, microbial activity evaluation, and rigorous risk assessment of potential leakage pathways. With appropriate technical and regulatory frameworks, Libya's depleted hydrocarbon assets could be transformed into a strategic national asset for large-scale, seasonal, and long-duration energy storage, supporting both domestic decarbonization goals and international hydrogen export ambitions.

Table 2: Summary of main oil and gas fields in Libya [31-35].

No	Basin	Field	Discovery Year	Lithology	Production Fluid
1	Sirte	Bahi	1959	Sandstone	Oil
2		Dahra and Hofra	1958-1959	Carbonate	Oil and Gas
3		Zelten (Nasser)	1959	Carbonate	Oil
4		Amal	1959	Carbonate and Sandstone	Oil
5		Beda	1959	Carbonate	Oil
6		Waha	1960–1961	Carbonate	Oil
7		Defa	1961	Carbonate	Oil
8		Raguba	1960	Carbonate	Oil and Gas
9		Sarir "C" Main	1961	Sandstone	Oil
10		Jalu	1961	Carbonate and Sandstone	Oil
11		Samah	1961	carbonate and sandstone	Oil
12		Hateiba	1963	Carbonate	Gas
13		Sarir "L"	1964	Sandstone	Oil
14		Nafoora-Augila	1965-1966	Carbonate and Sandstone	Oil
15		Intisar"A	1967	Carbonate	Oil
16		Intisar D"	1967	Carbonate	Oil
17		Sabah	1964	Carbonate	Oil

18		Bu Attifel	1968	Sandstone	Oil
19		Messlah	1971	Sandstone	Oil
20		Mabruk	1959	Carbonate	Oil
21		Kalanshiyu	1965	Sandstone	Oil and Gas
22	Ghadames	Hamadah	1970s–1980s	Sandstone	Oil and Gas
23		Ghziel	1970s–1980s	Sandstone	Oil and Gas
24		Al Wafaa	1991 -1994	Sandstone	Gas
25		Hamra	1960 - 1967	Sandstone	Oil
26		Tigi	1958 - 1958	Sandstone	Oil
27	Murzuq	Atshan	1957	Sandstone	Gas
28		El Shararah	1984	Sandstone	Oil
29		El Feel	1997	Sandstone	Oil

4.1 Strategic Evaluation of Libyan Basins for Green Hydrogen Storage

The comparative analysis of the Sirte, Ghadames, and Murzuq basins identifies the Sirte Basin as the primary candidate for initial green hydrogen storage feasibility studies. This prioritization is based on the following three pillars:

4.1.1. The Sirte Basin: The Primary Strategic Hub

The Sirte Basin holds a clear advantage due to its unique combination of geological capacity and historical development:

a. Volumetric Capacity: It hosts giant-scale fields such as Zaltan, Sarir, and Messla, etc. These massive fields offer the significant subsurface volume required for industrial-scale hydrogen storage.

b. Geological suitability: Having been in continuous production since the 1960s, many fields are "mature" or "depleted." This is critical because depleted reservoirs have thick sedimentary sequences with well-documented seals (e.g., shales and evaporites) and pressure histories, reducing the geological risk of hydrogen leakage.

c. Logistical Integration: The basin is already serviced by an extensive network of pipelines and is situated in close proximity to the major export terminals of Zuwetina, Brega, and Sidra, facilitating rapid transition to international markets.

4.1.2. The Ghadames Basin: The Secondary Export Link

The Ghadames Basin ranks second in strategic importance, primarily as a bridge to the European market:

1. Direct Connectivity: The Wafa field is particularly vital due to its existing direct pipeline links to Europe (Greenstream), which could potentially be repurposed for hydrogen blending or dedicated transport.
2. Established Infrastructure: While smaller than Sirte, its several active fields provide a ready-made framework for regional storage pilots.

4.1.3. The Murzuq Basin: Future Potential, Present Constraints

The Murzuq Basin is currently the least suitable for immediate hydrogen storage initiatives due to several structural challenges:

1. Operational Youth: Its fields are relatively new and have not yet reached the stage of depletion or maturity required for optimal storage safety.
2. Low Field Density: There are fewer discovered fields compared to the Sirte Basin.
3. Geographic Isolation: Its remote inland location and distance from northern export ports significantly increase the "levelized cost of storage" (LCOS) due to the high cost of new pipeline infrastructure.

Table 3. Comparative evaluation of Libyan sedimentary basins for Underground Green Hydrogen Storage Potential.

Criteria	Sirte Basin	Ghadames Basin	Murzuq Basin
Number of Fields	Very high (numerous giant fields)	Moderate	Limited
Field Maturity	High (many fields since 1960s; mature to depleted)	Moderate (partially mature)	Low to moderate (relatively recent production)
Storage Capacity Potential	Very high (large mature andovermature fields)	Moderate to high	Limited
Infrastructure Availability	Available and extensive (pipelines, processing facilities)	Available but less extensive	Limited infrastructure
Proximity to Export Terminals	Close to Zueitina, Brega, Sidra terminals	Connected to Europe via pipelines (Wafa Field)	Far from main export terminals
Geological Suitability	Good	Good	Good
Economic Feasibility	High	Moderate	Low
Readiness for Hydrogen Storage	High (near-term candidate)	Medium (mid-term potential)	Low (long-term potential)
Overall Ranking	1st (Most Suitable)	2nd	3rd (Least Suitable)

5. Discussion

The findings demonstrate that Underground Hydrogen Storage (UHS) in Libya is supported by favorable geological conditions, particularly within depleted oil and gas fields. The proposed UHSSI framework establishes a structured and integrated methodology for evaluating storage suitability by combining structural, petrophysical, and geomechanical parameters. This approach addresses a significant methodological gap in UHS assessments across North Africa, where such integrated frameworks remain limited.

From a reservoir perspective, sandstone formations exhibit clear advantages due to their relatively homogeneous pore structures, predictable fluid flow behavior, and reduced geochemical reactivity with hydrogen. These characteristics enhance storage efficiency and reduce uncertainty during injection and withdrawal cycles. In contrast, carbonate reservoirs introduce higher levels of complexity, primarily due to their heterogeneity, diagenetic alterations, and fracture-dominated flow systems. Although carbonates may offer substantial storage capacity, their performance is less predictable, making them more suitable for later-stage evaluation rather than initial deployment.

Caprock integrity remains a critical factor in ensuring long-term containment. Evaporites and shale formations are particularly effective seals, as demonstrated by their ability to retain hydrocarbons over geological timescales. However, the behavior of hydrogen within these systems may differ from conventional hydrocarbons. Processes such as molecular diffusion, potential geochemical reactions, and microbially mediated hydrogen consumption introduce additional uncertainty, highlighting the need for targeted experimental and field-based studies.

Structurally, Libya benefits from relatively stable tectonic conditions and predominantly inactive fault systems, which significantly reduce the risk of hydrogen leakage. This geological advantage, combined with the presence of extensive existing petroleum infrastructure, enhances the technical and economic feasibility of implementing UHS projects. Nevertheless, several uncertainties remain unresolved, particularly regarding hydrogen rock interactions, microbial activity, and the long-term effects of cyclic injection withdrawal operations. These factors must be carefully evaluated prior to large-scale deployment.

In terms of site prioritization, the Sirte Basin emerges as the most suitable candidate for a Phase 1 green hydrogen pilot project. This is attributed to its well-characterized reservoirs, extensive infrastructure network, and strategic proximity to export terminals. The Ghadames Basin represents a viable secondary option, offering promising geological conditions but requiring further detailed assessment. Meanwhile, the Murzuq Basin is better considered a long-term prospect, pending additional exploration, reservoir maturation, and infrastructure development.

6. Conclusion

This study provides the first systematic geological framework for assessing underground green hydrogen storage in Libya, directly addressing a critical research gap. By evaluating the country's major sedimentary basins, we conclude the following:

A. **Viable Potential Exists in Depleted Reservoirs:** Libya is not a suitable candidate for salt cavern hydrogen storage due to the absence of required halite formations. However, its extensive inventory of mature and over-mature hydrocarbon fields, particularly sandstone-dominated reservoirs in the Sirte, Ghadames and Murzuq basins and certain carbonate reservoirs in the Sirte Basin, represent a significant and technically viable resource for UHS. These formations offer proven containment, favorable petrophysics (ϕ 15-30%, $k > 100$ mD), and robust regional seals.

B. **Repurposing is the Strategic Pathway:** The most pragmatic and economically sound strategy for Libya to enter the hydrogen storage market is the repurposing of its existing depleted oil and gas fields. This approach leverages sunk costs in infrastructure, de-risks subsurface uncertainty using legacy data, and offers the shortest path to pilot demonstration compared to developing saline aquifers.

C. **A Standardized Screening Framework is Required:** The proposed Underground Hydrogen Storage Suitability Index (UHSSI), integrating Caprock Potential (CPI), Reservoir Quality (RQI), and Site Potential (SPI), offers a science-based, risk-informed tool to screen and rank potential sites. Its application to Libyan basins successfully identified priority zones (e.g., high-porosity sandstones under thick shale and evaporate seals) and deprioritized high-risk features (e.g., fault-dense carbonate buildups without geochemical assessment).

D. **Technical and Economic Hurdles Remain:** While geological suitability is a necessary first step, significant challenges persist. These include the potential for geochemical reactions with carbonates and clays, microbiological hydrogen consumption, geomechanical risks from cyclic loading, and the high cost of cushion gas. Addressing these requires site-specific, integrated reservoir modeling and pilot-scale testing.

E. **Strategic Evaluation of Libyan Basins for Green Hydrogen Storage:** For a Phase 1 hydrogen pilot project, the Sirte Basin is identified as the most suitable candidate for green hydrogen storage in Libya, owing to its mature and in some cases depleted reservoirs, well-established infrastructure, and close proximity to major export terminals. The Ghadames Basin represents a viable secondary option, supported by existing pipeline networks and favorable reservoir conditions. In contrast, the Murzuq Basin is considered a longer-term prospect due to its relatively limited infrastructure, fewer developed fields, and lower reservoir maturity, which currently constrain its immediate applicability for hydrogen storage deployment. In summary, Libya's geological inheritance provides a strong foundation for becoming a regional player in the green hydrogen economy and will be good pathway to support Libya's transition toward a low-carbon energy system. However, realizing this potential requires moving beyond regional screening to targeted, data-intensive pilot projects that validate storage integrity and economic viability.

7. Recommendations

To advance the deployment of UHS in Libya, the following strategic actions are recommended:

A. Initiation of Pilot Projects: Select a high-ranking sandstone reservoir (e.g., within the Sarir or Messlah fields) for a small-scale pilot project to validate real-world hydrogen-rock-fluid interactions.

B. Infrastructure Audit: Conduct a detailed technical audit of existing "over-mature" wells and pipelines to determine their compatibility with hydrogen embrittlement and high-pressure cycling.

C. Detailed Geochemical Modeling: Perform site-specific laboratory analyses on core samples from the Sirte Shale and Tanezzuft formations to assess potential microbial activity and gas purity risks during storage.

D. Regulatory Framework Development: Establish national safety standards and regulatory protocols for UHS, leveraging international best practices while tailoring them to Libya's unique subsurface legalities.

E. Multi-Basin Mapping: Expand the use of the UHSSI to create a digital "Hydrogen Storage Atlas" for all major Libyan basins, providing a strategic roadmap for international investors and energy developers.

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