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DELIVERABLE 4.1

REPORT ON THE GEOLOGICAL AND RESERVOIR CONDITIONS OF THE UNDERGROUND STORAGE OF HYDROGEN AND THE POTENTIAL SYNERGIES OF UNDERGROUND GAS STORAGE SITES AND LESSONS LEARNT

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Underground Hydrogen Storage in Europe: Opportunities, Challenges, and Case Studies

Executive Summary

Underground hydrogen storage (UHS) is emerging as a critical component of Europe's clean energy transition, providing a means to buffer large quantities of energy to balance intermittent renewables. This report presents a comprehensive overview of UHS in Europe, blending general background, engineering considerations, and academic research insights. Key findings include:

- **Role in Energy Transition:** UHS enables *power-to-gas-to-power* schemes, where surplus renewable electricity is converted to hydrogen and stored underground, then re-electrified when needed. This flexibility helps stabilize energy supply and demand, supporting decarbonization targets. European strategies like the EU Hydrogen Strategy recognize green hydrogen as a clean fuel, spurring investments in its production and storage.

- **Suitable Geological Formations:** Hydrogen can be stored in porous rock formations (depleted oil/gas reservoirs and deep saline aquifers) or in engineered caverns in rock (especially salt caverns). Each option has distinct characteristics

    - **Salt Caverns:** Offer high injection and withdrawal rates and an essentially impermeable container for hydrogen. Salt formations in northern Europe are abundant (e.g. North Germany, UK, Netherlands), giving significant storage potential.

      Deep Saline Aquifers: Widespread and potentially large-scale, but require more characterization. Historical use of aquifers to store town gas (50–60% hydrogen) in Europe has demonstrated feasibility.

- **Technical Considerations:** UHS faces unique technical challenges. Hydrogen's low density and high diffusivity mean larger volumes are needed to store energy equivalent to natural gas, and careful sealing is required to prevent leakage. Cushion gas requirements differ by storage type (salt caverns need ~20–30% of volume as base gas, versus ~50% in depleted reservoirs). Material compatibility is crucial: hydrogen can embrittle steel pipelines and well casings, so suitable alloys must be used (recent tests have identified steel grades that perform well in hydrogen environments). Additionally, microbial reactions underground can consume a small fraction of hydrogen or generate contaminants (e.g. methane or H_2S), necessitating gas treatment on withdrawal

- **Economic and Environmental Factors:** Salt cavern storage is expected to have the lowest levelized cost for large-scale, fast-cycling hydrogen storage, thanks to high deliverability and minimal cushion gas needs. Depleted fields and aquifers offer lower upfront cost by leveraging existing geology, but may incur costs for cushion gas and purification of output gas. Environmentally, UHS

is considered safe when sites are properly selected and managed. Salt caverns have an excellent sealing record (used for natural gas for decades without leakage), and porous reservoirs used historically for town gas did not experience major issues, though continuous monitoring is required. Preventing hydrogen leakage protects both energy yield and mitigates any indirect greenhouse effects of hydrogen in the atmosphere. Overall, UHS allows long-duration energy storage with minimal land footprint, unlike above-ground storage which would require massive tank farms or expensive liquefaction and high cost safety measures.

- **Case Studies in Europe:** Several projects underscore the progress in UHS:
  - *Salt Caverns:* The HyPSTER project in Etrez, France – the EU's first renewable hydrogen salt cavern demonstrator – was inaugurated in 2023. By 2026 it aims to store ~50 tonnes of green hydrogen (≈1,650 MWh energy) to supply industrial and mobility uses. In the UK, SSE/Equinor are repurposing the Aldbrough gas storage (nine salt caverns) for hydrogen, targeting at least 320 GWh capacity by 2028, which would make it one of the world's largest H_2 stores. The Netherlands' HyStock pilot by Gasunie successfully injected hydrogen into a salt cavern at Zuidwending in 2021–2022, confirming that existing natural gas caverns can safely store hydrogen.

  - *Depleted Reservoirs:* RAG Austria's **Underground Sun Storage** project in a depleted gas field (Gampern, Austria) became the world's first field test of pure hydrogen storage in porous rock in 2023. Approximately 4.2 GWh of green hydrogen (from summer solar surplus) is stored and recovered in winter, proving seasonal storage in a real gas reservoir. This successful demo indicates that Europe's numerous depleted gas fields could be reutilized for hydrogen.

  - *Historical Examples:* Hydrogen-rich "town gas" (containing ~50% H_2) was stored underground in Europe in the 20th century. Notably, salt caverns at Teesside (UK) held 95% hydrogen gas mixture at 400 m depth without issue, and aquifer storages in Ketzin (Germany), Lobodice (Czech Republic), and Beynes (France) stored town gas for many years. These cases provide confidence in the geologic containment of hydrogen.

- **Regulatory and Policy Framework:** Currently, Europe lacks a dedicated, unified regulatory framework for hydrogen storage, which creates uncertainty for project developers. Efforts are underway to address this gap. The European Commission's Hydrogen Strategy (2020) acknowledges the need for long-term underground storage, and proposals in the Gas Package aim to integrate hydrogen storage into energy markets. Industry groups such as Gas Infrastructure Europe (GIE) and the "H_2eart" alliance are calling for explicit UHS targets and support mechanisms. A recent study recommends the EU set a **2030 target of ~45 TWh** of hydrogen storage capacity (versus only ~9 TWh in current projects), to align with climate goals. Closing this gap could save the energy system billions by 2050 through avoided infrastructure and fuel costs. Key policy needs include simplifying permitting procedures, providing investment incentives or contracts for storage, and ensuring hydrogen storage is recognized and remunerated for the system flexibility it provides. Some European countries have begun adapting regulations (e.g. defining hydrogen quality standards and blending limits in pipelines), but a clearer EU-wide framework would accelerate UHS deployment.

- **Greece Focus – Potential UHS Sites:** Greece is actively evaluating its underground hydrogen storage potential. Geological studies identify several promising sites:
    - **Salt Caverns (Evaporites):** Thick Triassic in age evaporite formations exist in Greece that could host salt cavern storage. Notably, bedded salt deposits in the Ionian Islands (Corfu and Kefalonia) are deemed suitable for hydrogen caverns. A recent assessment modeled that a single cavern in these salt formations (~550,000 m³ volume at 650 m depth) could store about **80 GWh** (~26.6 GWh) of hydrogen. Corfu and Kefalonia together could thus hold ~53.2 GWh, enough to meet the annual electricity needs of ~6,770 households. On Crete, a major salt formation near Heraklion is also noted (Messinian age), though likely more viable for natural gas storage due to infrastructure location. Deep geological description and characterization is needed.

    - **Depleted Gas Fields:** Greece has a few small hydrocarbon fields, such as **Prinos** and **South Kavala** (offshore in the North Aegean). These fields are candidates for underground gas storage (UGS) and, in the future, possibly hydrogen storage once depleted. South Kavala is being developed as a strategic gas storage facility; if converted to hydrogen later, its geology (a sealed dome reservoir) could be repurposed similarly to European gas fields. Additionally, onshore gas fields like *Epanomi* (Thessaloniki region) and *Katakolo* (West Greece) could be evaluated for H_2 once their hydrocarbons are exhausted, but they have not been developed yet.

    - **Other Formations:** Certain sedimentary basins in Greece contain deep porous aquifers that might support hydrogen storage. The Mesohellenic Trough and Western Thessaloniki basin are among them, have extensive porous sandstones and were highlighted for natural gas, CO2 and possibly hydrogen storage potential. However, aquifer storage would require thorough feasibility studies (no specific hydrogen aquifer pilot has been done in Greece yet). A first attempt to compile a CCS storage Atlas for Greece with particular focus in the Mesohellenic Trough has been recently made by Gaganis et al. (2025).

The Hellenic government is moving forward on these fronts. In July 2024, the Hellenic Survey of Geology & Mineral Exploration (HSGME) and the national energy resources company (HEREMA) signed an agreement to identify and utilize geological sites for energy storage, including hydrogen storage in both underground reservoirs and caverns. This initiative will map Greece's geology (from old hydrocarbon exploration data and new surveys) to pinpoint salt layers or depleted fields that could be developed for UHS. The inclusion of hydrogen storage in Greece's National Energy and Climate Plan signals growing policy support. Challenges remain – Greece's geology is not as flush with large salt domes as Northern Europe – but the combination of smaller salt deposits, aquifers and depleted gas fields could provide strategic hydrogen storage for the country's future hydrogen economy.

- **Challenges and Outlook:** While technically feasible, UHS must overcome several challenges to realize its full potential:

  - ***Technical Uncertainties**:* Long-term effects of cycling hydrogen in porous rocks (e.g. repeated pressurization on caprock integrity, or mineral reactions) are still being researched. Large-scale trials like Hystories indicate no major barriers, but further pilot projects will build confidence. Continued R&D is needed on materials (e.g. compressors, seals, and metallurgy for H_2 service) and on mitigating microbial activity (which appears low – on the order of 0.001–0.01% losses over seasonal cycles – but must be controlled to maintain hydrogen purity).

  - ***Economic Viability**:* UHS projects involve high upfront capital – solution mining caverns or reworking old wells – without established market revenue streams yet. The business case for hydrogen storage depends on future hydrogen price volatility and the value of flexibility. Policy support (grants, capacity payments, or inclusion in capacity markets) may be required initially. However, in the long run, as Europe's hydrogen production scales up, UHS can provide cost-effective seasonal storage unmatched by any other technology (for context, models project ~300 TWh of hydrogen storage may be needed in EU by 2050 for a net-zero system).

  - ***Regulatory Progress:*** Clear regulations and standards are essential to streamline project development. Definitions of hydrogen storage in energy law, rules for conversion of gas assets to hydrogen, and safety standards for hydrogen in underground settings are still evolving. EU-level coordination can ensure consistent safety and environmental safeguards. Notably, safety studies so far show that salt caverns can store hydrogen as safely as natural gas, and existing gas storage sites can be converted with appropriate modifications.

  - ***Public Acceptance**:* Gaining local support for UHS sites will be important. Public perception of hydrogen (a flammable gas) in the subsurface can be addressed by highlighting successful precedents and inherent safety features (e.g. deep underground isolation, multiple geological sealing layers, monitored operations). Transparent communication and community benefits will help in this regard.

Despite these challenges, the outlook for UHS in Europe is highly positive. Storage operators and research consortia (e.g. HyStorIES, HyUSPRe) have already identified thousands of potential storage sites across Europe, collectively capable of storing many tens of thousands of TWh of energy as hydrogen. Even a fraction of this capacity would enable renewable energy to fully replace fossil fuel seasonal supply swings. Moving forward, small-scale pilots (like HyPSTER and Underground Sun Storage) are paving the way for full-scale projects by proving technology and informing regulations. As renewable hydrogen production ramps up under EU initiatives, UHS will provide the necessary buffer to ensure energy security and grid stability.

In conclusion, underground hydrogen storage stands as a cornerstone technology for a carbon-neutral European energy system. By leveraging suitable geology – from bedded salt deposits to depleted gas fields – Europe can develop a robust hydrogen storage network. This will enable the continent to store surplus summer solar and wind energy as hydrogen and retrieve it in winter or during demand peaks, thereby coupling the gas and electricity systems in a sustainable loop. With ongoing R&D, supportive policies, and knowledge-sharing from early projects, the coming decade is expected to witness the scaling of UHS from pilot projects to an integrated pan-European infrastructure, including potential sites in Southern Europe (such as Greece) that broaden the geographic reach of hydrogen storage. UHS's benefits in flexibility, reliability, and decarbonization make it a strategic priority as Europe marches toward its 2030 and 2050 climate and energy goals.

Introduction: Role of Underground Hydrogen Storage in the Energy Transition

The global shift to carbon-neutral energy has intensified interest in green hydrogen as a versatile energy carrier. Hydrogen can be produced from renewable electricity and later used in fuel cells, turbines, or industrial processes without direct emissions. However, a critical challenge is *timing mismatch*, renewable generation fluctuates daily and seasonally, while energy demand may not align (Ma et al. 2024). This is where underground hydrogen storage (UHS) becomes pivotal. By storing large quantities of hydrogen in geological formations, surplus renewable energy can be banked and retrieved on demand, enabling continuous energy supply. The concept parallels the role of natural gas storage in today's energy system: balancing supply and demand on hourly to seasonal timescales.

Underground storage offers massive capacity compared to above-ground methods. Compressed hydrogen tanks or liquid hydrogen vessels are feasible for short-term buffering but become impractical for the multi-gigawatt-hour scale needed for seasonal storage (Elrhoul, Romero Gómez, and Naveiro 2023) . Figure 1 (Moore and Shabani 2016) illustrates the range of storage technologies by capacity and discharge duration. Above-ground options (like batteries, pressurized tanks, or liquid air storage) provide fast response but are limited in energy volume. In contrast, underground options – salt caverns and porous reservoirs, achieve far greater capacities and long discharge durations, measured in weeks to months. Underground hydrogen storage uniquely enables multi-terawatt-hour seasonal shifting of energy, something no other storage technology currently offers.

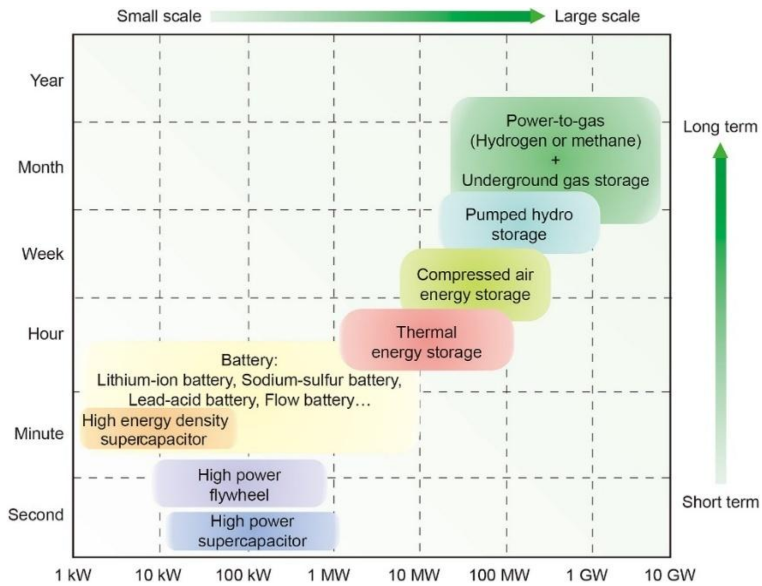

Figure 1 Comparison of energy storage technologies by capacity and discharge duration (Moore and Shabani 2016)

Beyond balancing renewables, UHS offers several benefits in the energy transition:

- **Grid Flexibility:** Large-scale hydrogen storage allows excess power (e.g. from a windy night or summer solar peak) to be stored and later converted back to electricity, effectively creating a long-duration buffer for the power grid . This mitigates curtailment of renewables and provides backup during lulls in wind/solar output (Quintos Fuentes and Santos 2023).

- **Energy Security:** Stored hydrogen acts as a strategic reserve of energy. Just as natural gas storage is used today to ensure winter supply in Europe, hydrogen storage can ensure continuity of energy supply from hours to an entire season of high demand. It improves resilience against supply disruptions and seasonal demand swings (Ma et al. 2024).

- **Sector Coupling:** Hydrogen can decarbonize sectors that are hard to directly electrify (industry, heavy transport, heating). UHS enables a steady hydrogen supply to these sectors even when renewable generation fluctuates. By linking the electricity grid with gas infrastructure (power-to-hydrogen and hydrogen-to-power), UHS facilitates sector coupling in a future integrated energy system (Giehl et al. 2023).

- **Emissions Reductions:** With UHS in place, countries can rely more on domestic renewable energy year-round, reducing reliance on imported fossil fuels. Hydrogen produced from summer oversupply can replace fossil fuels in winter, significantly cutting seasonal carbon emissions. Furthermore, underground storage has minimal surface footprint and zero direct emissions during operation (Wu et al. 2023).

In Europe, these advantages have been recognized at the policy level. The EU Hydrogen Strategy (2020) explicitly mentions the need to explore “long-term large-scale storage” to support a future hydrogen economy(Ma et al. 2024) . Following the

Paris Agreement and European Green Deal, many governments are adopting hydrogen roadmaps that include storage. The European Commission's approval of green hydrogen as a clean energy vector has already led to increasing investments in hydrogen infrastructure. Consequently, attention is turning to geological storage as a key enabler. The European Union's Clean Hydrogen Partnership has funded projects like HyStorIES ("Hydrogen Storage in European Subsurface") to assess potential sites and address research gaps. According to the HyStorIES findings, underground hydrogen storage could contribute immensely to EU climate neutrality by 2050, with no major technical showstoppers identified and a vast theoretical capacity across member states.

However, deploying UHS at scale is not trivial. It involves multidisciplinary challenges geology, engineering, microbiology, materials science, economics, and regulation, which this report will examine in detail. The subsequent sections provide an in-depth look at suitable geological formations, the technical, economic, and environmental considerations of UHS, real-world case studies in Europe, the prevailing regulatory framework, and a focused analysis of potential UHS sites in Greece as a case within Europe (Ajanovic, Sayer, and Haas 2024). Finally, we discuss the broader challenges and outlook for underground hydrogen storage as Europe pioneers this critical infrastructure for the clean energy era.

Geological Formations Suitable for Underground Hydrogen Storage

Underground hydrogen storage can take place in a variety of geological formations, broadly categorized into porous media and rock caverns (Tarkowski 2019) . Each type offers a distinct way to contain hydrogen and has its own set of geological criteria

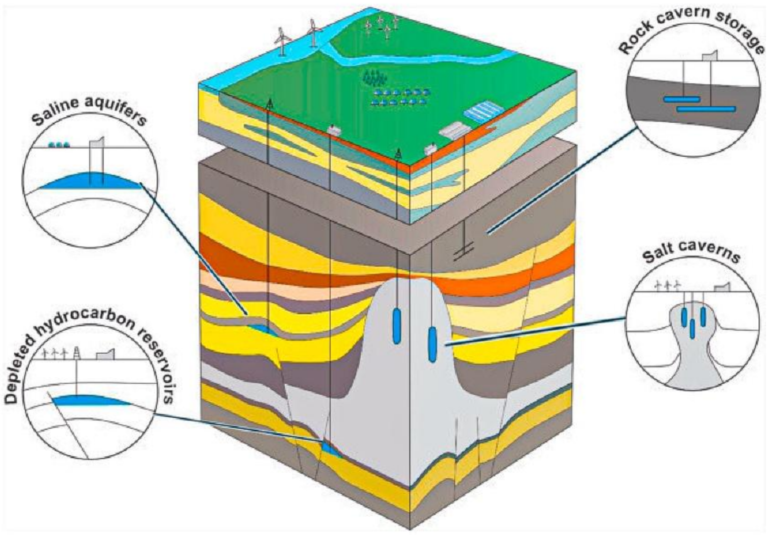

Figure 2 Geological Formations Suitable for Underground Hydrogen Storage (Jansons et al. 2025)

- **Porous Media:** These are reservoirs where fluids (gas or liquid) occupy the pore spaces of rocks. For hydrogen storage, the relevant porous media are:
  - **Depleted Oil and Gas Reservoirs**: Underground formations that have held hydrocarbons (natural gas or oil) and are now largely emptied of

producible fuel. They typically consist of permeable sedimentary rocks (e.g. sandstones or carbonates) with an overlying impermeable caprock that trapped the hydrocarbons. Such reservoirs are prime candidates for hydrogen storage because they are *proven sealers* (they held gas for millennia) and already have wells and geological data from hydrocarbon operations. Hydrogen can be injected into the same pore space once occupied by gas. Depleted gas fields are especially attractive since they often still contain some cushion of natural gas that can aid in maintaining pressure. Europe has many depleted fields, onshore and offshore, which represent a large potential storage volume.

- **Deep Saline Aquifers**: These are porous rock formations filled with brine (salty water) that have no commercial hydrocarbons. They are widely distributed and can be very large in extent and thickness. In aquifer storage, hydrogen would displace brine in the pores. Aquifers can provide massive capacity where other options are not available, although their geology is less characterized than known gas fields (Kanaani, Sedaee, and Asadian-Pakfar 2022). Historically, some aquifers were used to store manufactured gas (town gas), for example, the Beynes aquifer in France, demonstrating that gas can be contained in water-bearing structures. Key requirements include a good caprock (to trap the hydrogen below) and manageable geochemical interactions between hydrogen, brine, and minerals.

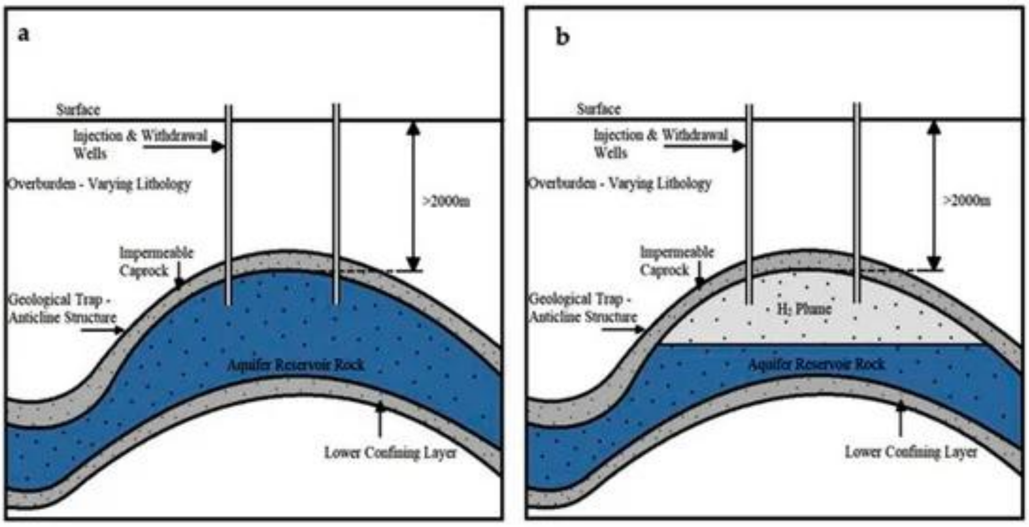

Figure 3: Aquifer structure before (a) and after (b) hydrogen storage (Jansons et al. 2025)

- **Rock Caverns:** These involve creating a man-made cavern in rock to hold hydrogen as a *pressurized gas*. There are sub-types based on the host rock:
  - **Salt Caverns**: By far the most prominent and commercially used option for UHS among rock caverns. Salt caverns are developed in thick deposits of rock salt (halite), typically by solution mining: water is injected to dissolve salt and the brine is pumped out, leaving a cavern. Salt is extremely impermeable and self-sealing; fractures in salt will creep closed under geologic pressure (Foh et al. 1979). This makes caverns

gas-tight containers, an ideal quality for hydrogen storage. Salt caverns can also handle many injection–withdrawal cycles and allow rapid flow rates due to their smooth, insoluble walls. They range in depth (commonly 500–1500 m) and size (a single cavern's volume is often 50,000–800,000 m³). Salt caverns have been used for decades in Europe to store natural gas, and trials have shown they can safely store high-purity hydrogen as well. Geological salt formations in Europe include bedded salt layers (e.g. in the North German Basin, Danish Basin, Polish Basin) and salt domes or diapirs (common in northern Germany, Netherlands, UK, and under the North Sea). Figure 2 shows the distribution of major salt cavern storage prospects across Europe. Regions with extensive salt (shaded by energy storage density potential) correspond to high UHS potential (Caglayan et al. 2020).

- **Lined Rock Caverns (LRCs)**: These are artificial caverns excavated in hard rock (such as granite or schist) and lined with a special membrane or steel liner to make them gas tight. LRCs have been developed for storing natural gas or compressed air in a few projects, and in principle could be used for hydrogen. They can be sited in regions without suitable salt deposits (Ripepi 2018). However, the construction cost is high (involves mining and lining), and thus LRCs are considered only if other options are unavailable. Development is at pilot stage in some countries (e.g. a pilot LRC for hydrogen in Sweden has been discussed in literature). We note LRCs for completeness, but they are not yet a focus in Europe's hydrogen plans due to cost (Tengborg, Johansson, and Durup 2014).

- **Unlined Rock Caverns & Mines:** Abandoned mines, especially deep coal mines, have been proposed for gas storage. In the past, some town gas storage was done in mines (and in lined wells) on a small scale (Rathnayaka and Ranjith 2024). For hydrogen, an abandoned mine would have to be carefully sealed and would inherently operate at lower pressures (to avoid leakage through fractures), limiting capacity. Current research is exploring using mines mainly for thermal energy storage or hydrogen *liquid fuel* storage, rather than bulk hydrogen gas, due to these limitations. Thus, disused mines are not primary candidates for large-scale hydrogen storage, though they could potentially serve niche uses or research testbeds (Qian et al. 2025).

In Europe, salt cavern storage is often highlighted as the preferred near-term option for hydrogen due to its high cycling capability and the well-established technique (adapted from natural gas storage). Studies show that salt caverns allow higher injection and withdrawal rates than porous reservoirs, meaning they can rapidly charge or discharge hydrogen to follow demand peaks (Qian et al. 2025) . This high deliverability is crucial for buffering daily fluctuations and providing grid balancing services. Additionally, salt cavern storage typically requires a smaller fraction of the gas to remain as *cushion gas* (base gas that stays in the cavern to maintain pressure) – on the order of 20–30% of the total volume – whereas porous reservoirs might need 50% or more to remain in place. The low cushion requirement makes salt caverns efficient in terms of working gas capacity (Zamani and Knez 2024) .

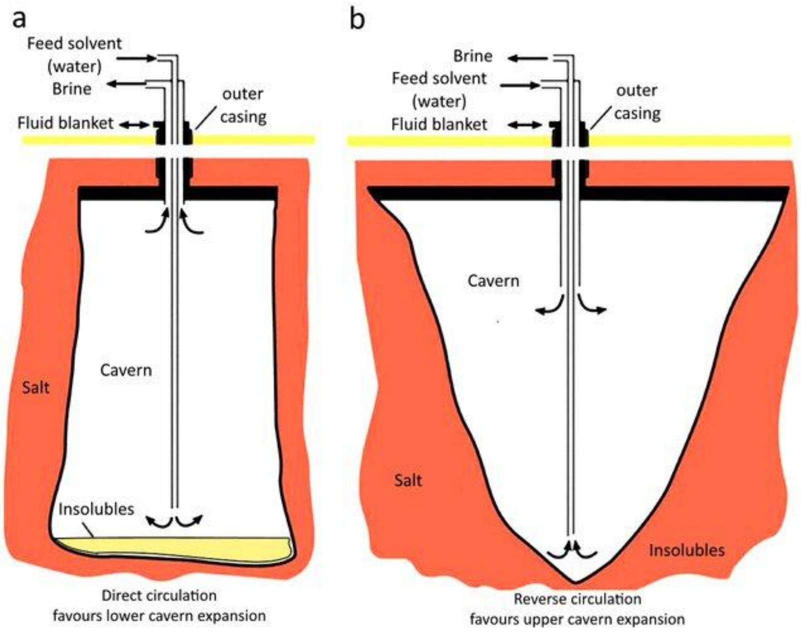

Figure 4 UHS in salt caverns with two configurations for creating and enlarging the cavern (Hematpur et al. 2023)

That said, porous reservoirs (depleted fields and aquifers) offer sheer scale. A single large gas field can hold many times the hydrogen of a single cavern (Song et al. 2025). Europe's salt caverns are inherently limited by suitable geology and cavern size, whereas porous reservoirs are more plentiful. Moreover, converting a depleted gas field to hydrogen storage can be cost-effective: much of the site characterization (e.g. reservoir extent, caprock integrity) is already done, and infrastructure like wells and compressors may be repurposed. An example is the large offshore gas fields in the North Sea, studies are examining whether parts of these fields, once production ends, could serve for hydrogen storage to support countries like the UK (Harati et al. 2024), Netherlands (Jaarsma et al. 2024), or Norway (Emmel et al. 2023) in balancing their future hydrogen supply. One technical caveat is that any residual methane in a depleted field will mix with the stored hydrogen; over time and multiple cycles, this needs management (either via initial flushing or accepting a hydrogen-methane blend) (Slabon 2025). We will delve into these issues later, but from a geological perspective, if a reservoir held methane, it could likely hold hydrogen – the main questions become engineering and chemical (how to handle the differences in gas properties).

Aquifers, being less characterized "greenfield" sites, might be tapped in regions without other options. In Europe, a famous historical example is the Gaz de France storage at Beynes, which successfully stored town gas (circa 50–60% hydrogen) in a deep aquifer near Paris for decades (Hugout 1997). Similarly, aquifer structures were used at Ketzin in Germany (Febbo et al. 2025) and Lobodice in Czech Republic (Tremosa, Jakobsen, and Le Gallo 2023) for town gas storage . These experiences indicate that given a good trap and caprock, aquifers can retain hydrogen-rich gas. Modern projects like the EU-funded HyUSPRe (Hydrogen Underground Storage in Porous Reservoirs) are studying the potential of both depleted fields and aquifers across Europe. The initial preference is to use known gas fields, but if Europe's hydrogen economy grows to very large size, saline aquifers could be called upon to supplement storage capacity. Aquifers also underlie some areas (e.g. parts of Eastern

Europe or France) where salt caverns are absent, providing a geographically distributed storage option.

Technical Considerations

Storing hydrogen underground entails a range of technical considerations that influence design, operation, and performance. These include the behavior of hydrogen gas under reservoir conditions, interactions with reservoir materials, cycling dynamics, and surface facility requirements. Below we discuss the key technical factors:

1. Gas Properties and Storage Mechanics: Hydrogen has unique physical properties compared to natural gas (methane)as it is a much smaller molecule, less dense, and has different thermodynamic behavior. Hydrogen's low **molecular weight** means that at a given pressure and temperature, it contains less energy per unit volume than methane. For example, at typical storage conditions (~100 bar, moderate temperature), hydrogen's energy density might be only about 1/3 that of natural gas. This implies that to store an equivalent amount of energy, a larger volume (or higher pressure) is needed for hydrogen. Engineers must account for this by either using bigger caverns/reservoirs or operating at as high a pressure as the geology safely allows(Chen et al. 2023).

Hydrogen's low viscosity is a double-edged trait: it can flow through porous media more easily (good for injectivity and deliverability), but it can also leak through tiny pathways that might confine denser gases. Fortunately, studies indicate that in intact reservoirs or salt caverns with proper caprocks, leakage will be minimal (Hashemi, Sedaee, and Fathi 2025). For instance, an analysis in the Hystories project modeled diffusive losses of hydrogen through caprock and found on the order of 0.004% loss over five seasonal cycles in a field-scale reservoir as essentially negligible. Hydrogen's diffusivity is higher than methane's, but caprocks (e.g. clays, evaporites) tend to be so impermeable that diffusion rates remain extremely low (Ghasemi et al. 2022) . Still, each storage site must ensure containment: thorough geomechanical assessment is done to check that fractures won't open at operating pressure and that any existing wells are properly sealed to prevent leaks (Antwi, Amber, and Oluyemi 2025).

Another aspect is thermal effects. When gas is rapidly withdrawn or injected, it cools or heats due to expansion/compression (Joule-Thomson effect). Hydrogen has different thermal properties and heat capacity than methane. Cavern operations must consider temperature changes in the gas which can affect cavern rock stability. However, since hydrogen has a higher thermal conductivity, it can exchange heat with rock faster, somewhat buffering temperature swings. In practice, the thermal behavior is manageable with proper flow rate control and was not found to be a showstopper in trials (Siddiqui and Ennis-King 2025).

2. Cushion Gas and Deliverability: All underground gas storages require some *cushion gas* to maintain reservoir pressure for deliverability. A notable technical consideration is what gas to use as cushion and how much is needed (Prigmore et al. 2024). In salt caverns, typically the cushion gas is the same stored gas (hydrogen in this case). Because salt caverns are effectively impermeable, operators can recover most of the hydrogen, leaving perhaps 20% as permanent cushion to keep minimal pressure . Some recent studies propose using an inert gas (like nitrogen) or even natural gas as a cushion under the hydrogen to reduce the amount of hydrogen left in place (Prigmore et al. 2024) . For instance, hydrogen could be floated on a layer of nitrogen in a cavern, given their density difference, to act as a buffer that prevents the hydrogen from contacting the cavern floor/brine. Experiments have shown this could work, and one benefit is if hydrogen purity needs to be maintained, a non-reactive cushion can help (Ramsari et al. 2025).

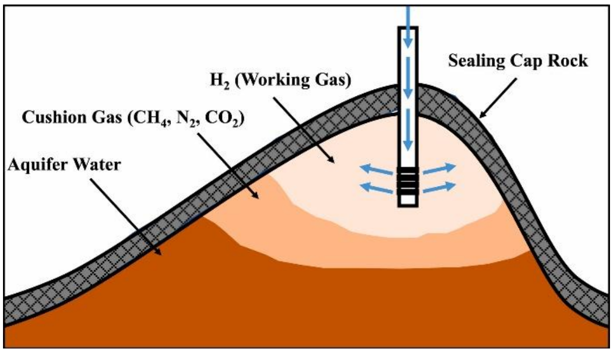

Figure 5 Schematic of underground hydrogen storage and formation of cushion gas in an aquifer (Saeed and Jadhawar 2024)

In depleted reservoirs and aquifers, a larger cushion fraction is needed. The porous medium requires sufficient pressure to deliver gas at the well, so a significant portion of the gas stays in the formation. Estimates often cite ~50% of the total gas volume as cushion for depleted fields (Al-Hussainy, Ramey Jr, and Crawford 1966) .The natural gas then acts as cushion. This has two implications: (a) It saves having to use pure hydrogen as cushion (which is expensive to leave idle), and (b) it means the first withdrawals will produce a hydrogen-methane mix until the methane is largely produced out. Over multiple cycles, the hydrogen fraction would increase (Ramsari et al. 2025). Another proposed cushion is carbon dioxide in some cases, which is cheap and could be left in the reservoir permanently beneath the hydrogen. Each cushion gas option requires ensuring it doesn't chemically interfere (CO_2 could react with rock or water; methane is mostly inert but affects purity). So far, the consensus is to use existing methane where possible, and otherwise perhaps nitrogen, as cushion gas for porous storages (Prigmore et al. 2024).

The deliverability (injection/withdrawal rate) depends on both the geology and the surface facilities. Hydrogen, having lower density, will result in higher flow rates for a given pressure differential through the same rock permeability (i.e. it's easier to push through pores). This can make hydrogen reservoirs very deliverable in volumetric terms (m^3/day). However, because each cubic meter has less energy, the energy withdrawal rate may be lower. One modeling study showed that in each gas field, the *mass flow* of hydrogen could be up to ~7 times lower than natural gas for the same pressure drop, due to hydrogen's low density. This means to get equivalent energy out, one might need more wells or higher-pressure operation. Nonetheless, hydrogen storages can still deliver enormous power output. For example, the planned Aldbrough hydrogen storage (salt caverns in UK) aims for ~320 GWh of energy; if withdrawn over, say, 10 days, that's ~1.3 GW output – a substantial contribution to grid peaking power. Deliverability is also enhanced by hydrogen's fast flow in wells (lower friction losses in pipe due to low viscosity). In salt caverns, the limiting factor is usually the well diameter and the surface equipment rather than the cavern itself, since caverns can expel gas rapidly as the large void allows pressure to push out gas quickly (like air rushing out of a balloon) (Al Homoud 2024).

3. Materials and Infrastructure: A critical technical area is the compatibility of existing infrastructure with hydrogen (Ugarte and Salehi 2022):

- **Wellbores:** Depleted reservoirs come with existing wells (which is an advantage cost-wise), but those wells must be reviewed. Cement and steel in well casings can be vulnerable to hydrogen. *Hydrogen embrittlement* is the process where hydrogen atoms diffuse into steel, especially high-strength steels, and make them brittle (Ugarte and Salehi 2022). This can potentially cause cracks or failures in pipes, valves, or casing over time. Research and field experience so far indicate that using appropriate steel grades (with certain alloy compositions or coatings) can mitigate embrittlement. The Hystories project, for instance, tested a dozen common oilfield steel grades in pressurized hydrogen and provided recommendations – presumably favoring lower-strength, more ductile steels or those treated to resist embrittlement. Additionally, maintaining some methane or using inhibitors can reduce hydrogen entry into metals (Bin Abed 2024).

- **Surface Facilities:** Compressors and turbines that handle hydrogen need special design. Hydrogen's molecular size means seals have to be tighter to prevent leaks (Salmachi et al. 2024). Compression of hydrogen also takes more stages because of its thermodynamic curve (it heats up quickly when compressed). Many companies (in industrial gas sector) have compressors for hydrogen but scaling them up for cavern injection is an engineering challenge. Turbo-compressors used for natural gas may need redesign (e.g. different impellers) for hydrogen service due to different sonic velocity of H_2. Moreover, the energy required to compress hydrogen is higher per unit of energy stored compared to methane (because you're moving more volume for the same energy) (Sheianov, Xiao, and Sun 2024).

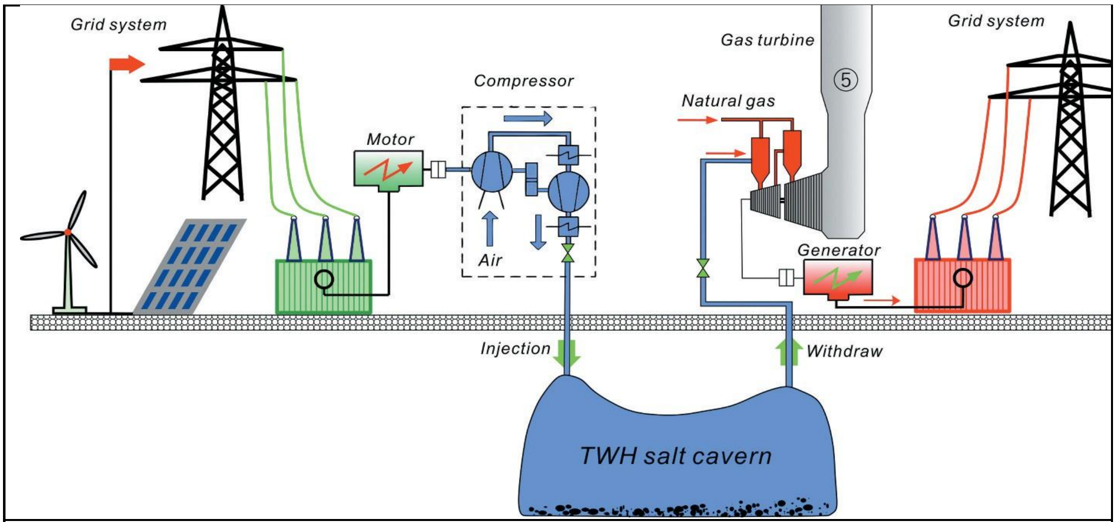

Figure 6 Schematic of surface facilities fo UHS (Salmachi et al. 2024)

- **Monitoring and Safety Systems:** Hydrogen is colorless and odorless like natural gas, but it has a wider flammability range in air and lower ignition energy (Okoroafor 2024). While underground, these factors are irrelevant (no oxygen down there), but at the wellhead and facilities, safety sensors (hydrogen detectors) must be in place. Materials like elastomer seals and valves need to be hydrogen-rated to avoid leakage. Protocols developed in industrial hydrogen handling (like at refineries or chemical plants) are being transferred to UHS operations. One advantage at site: since hydrogen is much lighter than air, if a small leak occurs at ground level it disperses upwards quickly (as opposed to propane or CO_2 which pool). Still, safety engineering is paramount to ensure any venting or leakage is promptly detected and handled (Devin et al. 2025).

4. Geochemical and Microbiological Interactions: When hydrogen is introduced into the subsurface, it can interact with the rocks, residual fluids, and microorganisms (Al-Yaseri, Amao, and Fatah 2023):

- **Rock Reactions:** Hydrogen is generally inert with most silicate minerals, but it can be reactive in the presence of certain compounds (Al-Yaseri et al. 2023). For example, if a reservoir has minerals like sulphates (anhydrite) and there are sulphate-reducing bacteria, those bacteria could use hydrogen to reduce sulphate to sulphide (producing H_2S gas, a toxic and corrosive gas). This is one of the main geochemical concerns: the generation of hydrogen sulfide (Braid et al. 2024). Past town gas storages did observe some H_2S production and had to implement gas purification. Mitigation involves ensuring low sulphate content or using biocide treatments. On the upside, any H_2S produced would likely stay in low concentrations if monitored, and can be removed by scavenger chemicals at the surface (Chang, Dempsey, and Huang 2026).

  Hydrogen can also reduce metal oxides in rocks (e.g. Fe^{3+} to Fe^{2+}), potentially altering rock chemistry. For instance, there's research indicating hydrogen might react with redbed sandstones by reducing hematite (iron oxide) to magnetite, but this is a slow process and not seen as a major issue for storage timescales (Braid et al. 2024).

- **Microbial Activity:** Subsurface microbes, if they encounter hydrogen, might treat it as a food source. There are methanogenic archaea that can consume H_2 and CO_2 to produce methane (CH_4), effectively *scrubbing* some hydrogen but yielding methane. Also, as mentioned, sulphate-reducing bacteria can produce H_2S using H_2 (Boon et al. 2024). These reactions not only alter gas composition but also consume hydrogen, reducing the storage efficiency. Lab and field tests, however, suggest that in deep reservoirs the microbial activity is limited by several factors: high salinity, lack of nutrients, and the short duration hydrogen is present seasonally. The Hystories project conducted experiments showing very low consumption rates – on the order of 0.06% in lab tests and 0.004% in field scale simulation over five cycles (Gao, Liu, and Elsworth 2024) . These small percentages indicate microbial impacts can be manageable. In one German field test (Underground Sun Storage project), some hydrogen did convert to methane (~2% turned to CH_4 over months), which the project saw as potentially useful (it created a renewable methane blend). Nonetheless, to maintain hydrogen purity, operators may consider sterilizing the formation (though hard on large scale) or just accept a small loss and handle it by separating methane on production (Vahabzadeh et al. 2025).

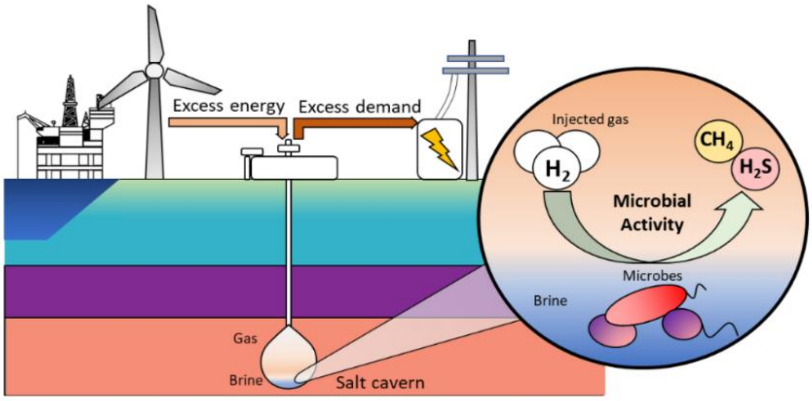

Figure 7 Schematic of occurrence of potential microbial activity in UHS (https://www.norceresearch.no/prosjekter/bio-risk-study-on-salt-caverns)

5. Cycling and Longevity: How frequently and extensively a storage is cycled (filled and emptied) influences design (Verma, Malik, and Pal 2025).

Salt caverns can handle frequent cycling (even daily) because the salt rock creeps slowly and can adjust to pressure swings. However, if you cycle very aggressively (large pressure changes daily), fatigue on the cavern and well could shorten life. Operators often restrict caverns to a certain maximum pressure swing for longevity. Caverns also “heal” – if pressure is kept high, salt creep closes fractures. They have very long potential lifetimes (decades of use, as seen in gas storage caverns) (Younes, Ghafouri, and Grasselli 2023).

Porous reservoirs have more inertia – they are usually used for seasonal storage (fill in summer, draw in winter) rather than daily arbitrage. This is because the large reservoir and its water need time to equilibrate; injecting and withdrawing too often can cause water encroachment issues and inefficient operations. That said, some depleted gas field storages do multi-cycle if they are high deliverability. But for hydrogen, likely these will be seasonal buffers. The longevity of a reservoir for storage could be essentially indefinite if managed (many gas storages in operation in Europe have been cycling for 40+ years). Key is monitoring that the reservoir or caprock isn’t degrading. Modern tools like microseismic monitoring can ensure no unexpected fracturing occurs(Bo 2024).

6. Surface Facility Integration: When designing UHS, one must consider the end-use of hydrogen (Gupta et al. 2023)

If hydrogen will feed a power plant, the withdrawal rates must meet the power plant’s intake needs (e.g. a 100% hydrogen gas turbine of X MW will require Y kg H_2 per hour storage must supply that). If hydrogen is for industrial or transport use, delivery pressure may need to be higher (to pipeline pressure or to truck filling pressure). Compressors at the withdrawal side may be needed. In some concepts, stored hydrogen might also be converted on-site to other carriers (like methanation to methane or to ammonia). But those are specific cases; generally, UHS is seen as part of a hydrogen supply chain involving pipelines (Oni et al. 2026). For example, hydrogen from storage can feed into the developing European Hydrogen Backbone pipeline network (Martin, Agnoletti, and Brangier 2020).

Economic Considerations

The economics of underground hydrogen storage are a decisive factor in its deployment. In evaluating economic viability, we consider capital costs (CapEx) to develop storage, operational costs (OpEx) to run it, and the overall value it provides to the energy system (which can be monetized through various market mechanisms or policy support) (Quintos Fuentes and Santos 2023).

1. Capital Costs of Developing Storage: These depend heavily on the storage type:

- **Salt Caverns:** The main CapEx elements are cavern creation (solution mining), surface facilities (wells, compressors, gas treatment), and connection to hydrogen infrastructure. Solution mining can be costly, it involves drilling a well and pumping large volumes of water to dissolve salt. Typically, it might take 1–2 years to create a large cavern, consuming water and producing brine that must be disposed (often by injecting into deep formations or the sea) (Haratian, Meybodi, and Dehvedar 2022). In regions where salt caverns already exist (from gas storage), conversion to hydrogen might only require cleaning the cavern and modifying surface equipment, which is cheaper than leaching new caverns. Industry estimates suggest salt cavern hydrogen storage can achieve relatively low levelized cost of storage (LCOS) for high cycling scenarios. A recent analysis projected that by 2030, salt cavern storage will be *the most cost-effective* solution for large-scale hydrogen, beating above-ground options on a per-kg stored basis. This is because caverns can store *huge* volumes once built, spreading the initial cost over a lot of hydrogen, and they have long lifetimes (Qian et al. 2025).

- **Depleted Reservoirs:** Many of the capital costs here are related to reworking existing infrastructure. Wells might need refurbishment or recompletion (to handle hydrogen), which is cheaper than drilling completely new wells. If a field has, say, 10 wells for gas production, those could be reused for injection/withdrawal with some modifications (new seals, maybe tubing replacements). Compressor stations will need to be built/upgraded for hydrogen service. Another cost could be cushion gas for salt, cushion is typically just part of operations, but for a reservoir you might need to buy a large volume of gas to leave in the ground. If using residual methane, that cushion cost is low (the methane is already there and presumably belonged to the field operator). If not, one might consider injecting some natural gas or N_2 as cushion which is cheaper than hydrogen. Nonetheless, early projects may have to fill reservoirs with significant hydrogen cushion, which is an investment (though not "spent," it's just locked in storage). On the plus side, not having to excavate a cavern saves cost (Haratian et al. 2022).

- **Aquifers:** Similar to depleted fields but often with more upfront exploration and testing costs since they haven't been characterized by oil/gas drilling. You effectively must do what oil companies do: exploration wells, reservoir modeling, etc., to establish an aquifer trap is secure. This makes initial costs higher and riskier (because you might drill and find it's not as good as thought). Thus aquifer storage might require a higher expected return to justify the exploration risk (Haratian et al. 2022).

2. Operating Costs and Cycles:

- **Compression energy:** To cycle hydrogen in and out, especially for salt caverns which might see frequent cycling, you spend electricity to run compressors. Hydrogen compression is energy-intensive; compressing to 200 bars can consume a few percent of the hydrogen's energy content. If electricity is cheap during surplus (which is often when you'd inject hydrogen), this cost can be low. Still, it affects round-trip efficiency and thus cost (Hu et al. 2024).

- **Monitoring and maintenance:** Similar to gas storage and maintaining wells, ensuring valves and instruments are working, monitoring gas composition (especially for porous storages) (Hu et al. 2024). For hydrogen, there may be additional costs for more frequent inspections due to embrittlement concerns, or for adding odorant (maybe not needed if the hydrogen is pure for industrial uses).

- **Cushion gas financing:** If you have, say, 50% of your reservoir as cushion that is hydrogen you purchased, that's a capital tied up. Economically, one can treat it as a one-time cost, but some analyses treat the *opportunity cost* of cushion gas as an operational cost (because it's capital that could have been used elsewhere). For hydrogen, if cushion is hydrogen, that's a big deal because hydrogen is valuable. But if cushion is something cheap, that mitigates it (Hu et al. 2024).

  Cycle frequency and utilization: The economics improve if the storage is utilized regularly (many cycles per year or at least full charge-discharge annually) (Jadhawar and Saeed 2023). If a storage sits mostly idle "just in case," it provides value as insurance but the cost per unit of hydrogen actually used is high. In early years of a hydrogen economy, storages might not cycle fully due to limited hydrogen surplus or demand swings. This raises a classic chicken-and-egg: storage is needed for a hydrogen market, but until the market is big, the storage might be underused. Some form of financial support or payments for standby capacity might be needed to bridge this gap(Harati et al. 2024; Quintos Fuentes and Santos 2023).

3. Value Streams and Market Structure: How can an underground hydrogen storage make money or justify investment?

In current natural gas markets, storage operators earn money through seasonal price arbitrage (buy gas in summer when cheap, sell in winter when expensive) and/or through reliability services (capacity payments, etc.). A hydrogen storage could similarly arbitrage electricity or hydrogen prices: e.g. charge when power is cheap (electrolyzers make H_2 at low cost), discharge when power or hydrogen is expensive (supply fuel to industry when other sources are pricey). The spread between low and high hydrogen price would determine profitability (Rademaker 2024). As renewables penetration grows, we do expect periods of extremely low or negative electricity prices (which translates to cheap hydrogen), and periods of high-power prices (making hydrogen valuable for re-electrification). Another revenue source is providing backup capacity. For instance, a hydrogen storage feeding a gas turbine that only runs at peak times could receive capacity payments from electricity markets for being available to generate, even if it's rarely used. The UK is exploring such models with its capacity market and how hydrogen plants/storage might participate (Harati et al. 2024).

4. Cost Comparisons:

- Salt cavern H_2 storage cost: dominated by cavern leaching CapEx. If a cavern can store, say, 5–6 tonnes of H_2 (roughly 200 MWh) and costs tens of millions of euros to develop, the cost per MWh capacity might be on par with building pumped hydro or large battery but with longer duration (Rademaker 2024). Studies (Alms et al. 2023) (e.g. from Germany's FZ Jülich) estimated salt cavern storage costs in the range of €0.2–1 per kg of hydrogen per storage cycle (excluding cost of hydrogen itself) depending on utilization. These are low.

- Depleted field H_2 storage: fewer references, but if repurposing an existing gas storage, the incremental cost is small. If building new in a depleted field, likely similar order of magnitude to salt caverns, perhaps lower if cushion gas is cheap (Kanaani et al. 2022).

- Lined rock cavern: likely several times more expensive than salt caverns per unit capacity, due to excavation costs. Not likely to be economical unless hydrogen prices are very high or there's no alternative in a region (Ripepi 2018).

A concrete example: The Aldbrough project (320 GWh) has not published a cost, but it involves building some new caverns. If we guess it's a few hundred million pounds project, the cost per kWh stored is quite low because 320 GWh is huge. Compare that to a Li-ion battery: 320 GWh of battery would cost astronomical sums (billions). Of course, batteries deliver electricity directly and with higher round-trip efficiency, so not a direct apples-to-apples, but it underscores that for multi-gigawatt-hour needs, geological storage is far more economical in terms of capital deployed (Hoth et al. 2023) .

5. Economic Challenges Specific to Hydrogen:
The price of hydrogen itself is currently high (green hydrogen can be €3-8 per kg in 2025 estimates) (Vaccaro et al. 2025). Losses or cushion tied up represent real value. If hydrogen prices drop in the future (with cheaper renewables and scale-up), it becomes easier economically to use hydrogen as the working gas. These projects are infrastructure with long paybacks. They require confidence in long-term regulatory treatment. Will hydrogen storage be regulated like gas storage (with some allowed returns) or entirely market-driven? This is to be determined (Zhao, Mao, and Mehana 2025).

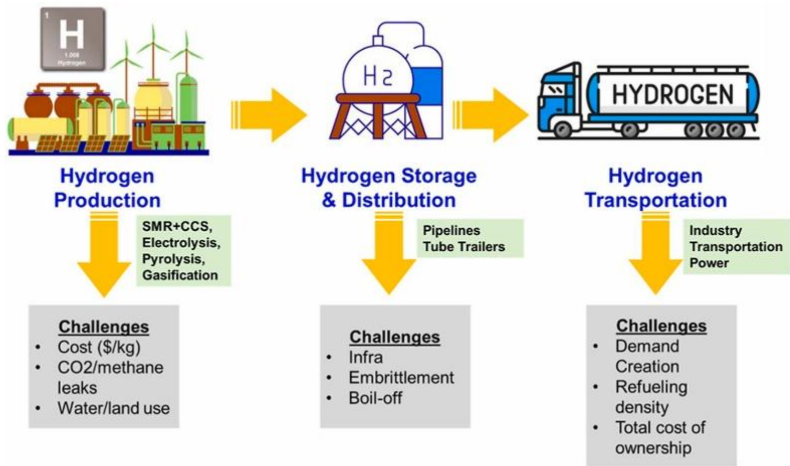

Figure 8 Challenges and future directions to improve the hydrogen economy (Brindhadevi, Kamarudin, and Pugazhendhi 2026)

Given these issues, many analyses (like the Aragon Hydrogen Foundation's commentary) emphasize the need for targeted support: e.g. grants, low-interest loans, or contracts that guarantee a certain return for storage operators. For instance, the EU's Innovation Fund is co-funding some first-of-a-kind projects like HyPSTER. National governments might include hydrogen storage in capacity mechanisms or strategic reserve schemes.

6. Macroeconomic Perspective: On a system level, the presence of UHS can reduce overall energy system costs by optimizing the use of renewables and infrastructure (Ugarte and Salehi 2022). During periods of oversupply, instead of curtailing wind/solar (wasting free energy), that energy is stored as hydrogen. During high demand, instead of firing expensive peaking plants or importing energy, stored hydrogen is used. A study by Frontier Economics for GIE (2023) quantified that failing to invest in hydrogen storage (leaving a gap of ~36 TWh in 2030 between needed and actual) would lead to higher costs and emissions as the system would rely on costlier alternatives. These alternatives might include more standby power plants, more interconnectors, or massive build-out of other storage like batteries which aren't economical for long durations. Therefore, while an individual project might struggle with profitability in early years, from a societal viewpoint, facilitating some hydrogen storage capacity is prudent and cost-saving in the long run (Zhao et al. 2025).

Environmental and Safety Considerations

Underground hydrogen storage, if well-managed, is considered a safe and environmentally benign technology. Many safety and environmental aspects mirror those of natural gas storage, with some differences due to hydrogen's properties.

1. Containment and Leakage Risks: The foremost environmental concern is the potential leakage of hydrogen from the storage formation. Unintended hydrogen migration could occur through faulty wells, through caprock if it's compromised, or via minor fissures in cavern walls (Hurtado et al. 2024). However, experience from natural gas storage shows that with proper site selection and maintenance, leaks are very rare. Salt caverns have an excellent record – the rock salt's self-sealing nature has prevented leakage even over decades. Depleted fields rely on the same geologic seals that held hydrocarbons for ages, so if they are structurally intact and wells are properly sealed, hydrogen should remain trapped (Hurtado et al. 2024).

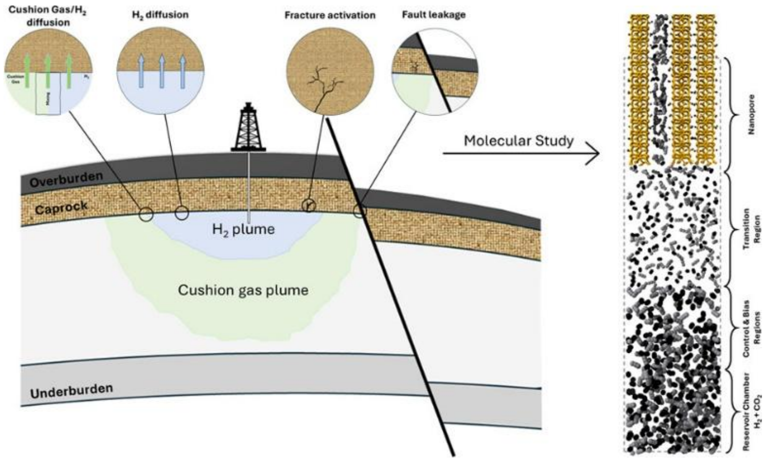

Figure 9 Risk of H2 Leakage into Caprock and the Role of Cushion Gas as a Barrier in H2 Geo-Storage (Kahzadvand et al. 2024)

In the unlikely event of a leak reaching the surface, hydrogen's environmental impact is much less severe than methane's: hydrogen is not a greenhouse gas in itself (though it can indirectly cause warming by elevating methane and ozone levels in the atmosphere). If a slow hydrogen seep occurred, it would likely diffuse into the air and harmlessly dissipate (hydrogen rapidly dilutes and escapes upwards due to being lighter than air). There is no toxic residue that hydrogen isn't toxic to breathe (the danger is only if it displaces oxygen in enclosed spaces). Contrast this with a CO_2 leak (which could asphyxiate) or a gasoline leak (which contaminates soil and water), hydrogen is relatively clean (Qian et al. 2025). The main risk of a large, rapid hydrogen leak is flammability/explosion if it accumulates in air in the flammable concentration range (about 4–75% H_2 in air). But underground, there is no oxygen, so combustion cannot occur at the source. At the surface, any vented hydrogen disperses quickly. To put risk in perspective: natural gas storage facilities have occasionally had leaks or blowouts; similar protocols (monitoring wells, surface gas detectors around the site) would be in place for hydrogen storage to catch any leaks early (Qian et al. 2025).

One environmental consideration is whether hydrogen might affect groundwater if it migrates out of the target zone. Hydrogen in water is not harmful per se (water already contains dissolved gases including H_2 in tiny amounts) (Rigas 2024). If hydrogen were to leak into shallow groundwater, the primary effect could be fostering growth of certain microbes (since hydrogen can be a nutrient for them). This could change the biochemistry of an aquifer (for instance, promoting methanogens or sulfate reducers, which might alter water quality by producing methane or sulfide). However, for hydrogen to reach shallow groundwater, multiple confinement failures would have to occur (the deep reservoir and caprock and shallow seals all failing). In practice, properly sited UHS is far below potable aquifers and separated by impermeable layers. Monitoring wells can be placed to ensure no upward migration (Iranfar et al. 2026).

As discussed in technical sections, one byproduct of storing hydrogen could be the generation of H_2S (hydrogen sulfide) if sulfate-rich brines and bacteria are present. H_2S is toxic and highly corrosive; its uncontrolled release would be an environmental and safety hazard (Chang et al. 2026). Fortunately, occurrences of H_2S can be contained within the reservoir if it forms, it stays with the gas and is produced together, then can be removed at the surface by chemical scavengers or amine treating. It's standard procedure in natural gas operations to handle H_2S (many gas fields contain it naturally), so that expertise translates to hydrogen storage (Braid et al. 2024). Continuous monitoring of gas composition will alert operators if any H_2S is appearing, allowing mitigation. Preventing conditions that create H_2S (e.g. by possibly treating the formation with biocides or not injecting into sulfate-rich layers) is part of storage design if needed. No other significant contaminants are expected from hydrogen; it doesn't form heavy hydrocarbons or anything. It may pick up a bit of moisture from reservoirs (which is why produced hydrogen gas will likely need drying before use).

5. Surface Facility Safety: Above ground, hydrogen must be handled carefully. Many safety measures are identical to those in the industrial hydrogen sector (Louie and Ehrhart 2024b):

- Use of hydrogen detectors in facilities, because humans can't smell hydrogen (unlike natural gas which typically has odorant added – though in a pure hydrogen economy odorants might contaminate fuel cells, so detection relies on sensors).
- Proper ventilation of any enclosures to prevent H_2 build-up.
- Electrical equipment rated as explosion-proof where hydrogen could be present (since a small spark could ignite a H_2-air mix).
- Training personnel in hydrogen safety (it burns with an almost invisible flame in daylight, etc.).

These are well-understood practices. Companies like Gasunie, for example, reported that storing hydrogen in their Zuidwending salt cavern pilot posed no greater safety issues than natural gas – they applied the same protocols and found it to be "safe, efficient and affordable" as per their project conclusions. Key takeaways were that existing safety principles for gas storage remained valid for H_2.

6. Long-Term Considerations: If hydrogen storage sites are eventually decommissioned, the environmental closure process would involve ensuring all wells are sealed, and the caverns or reservoirs are left in a safe state (e.g. filled with brine for caverns, which is stable). Salt caverns are often simply flooded with brine and sealed – the salt will naturally creep and close over decades, entombing whatever is inside (in this case just brine). Depleted reservoirs would just remain filled with cushion gas or brine. Thus, unlike some industrial facilities, a retired UHS site doesn't leave behind problematic waste. It's more about making sure no pathways for leakage exist post-closure (Prigmore et al. 2024; Salmachi et al. 2024).

7. Comparison to Alternatives: From an environmental perspective, using underground storage greatly reduces the need for large above-ground storage of hydrogen. Above-ground pressurized tanks or liquefied hydrogen tanks for similar capacities would require massive facilities, with greater potential exposure to accidents (since they're on the surface and near people). UHS relocates that risk deep underground, naturally shielded. For example, to store the energy equivalent of a salt cavern (let's say ~100 GWh), you would need on the order of 20,000 standard hydrogen tanks (at 50 bar) or multiple huge cryogenic LH_2 tanks – an impractical solution. The underground approach confines the hydrogen in geology, where even worst-case scenarios have limited external impact (Hurtado et al. 2024; Rigas 2024).

8. Regulatory Safety Framework: European regulations for underground gas storage (UGS) provide a foundation for hydrogen. The Seveso Directive (relevant for storage of dangerous substances) and national mining laws already cover natural gas storage facilities. These will be extended or adapted to hydrogen. Some differences are being addressed: for instance, defining hydrogen-specific safety distances and ventilation requirements. Germany, UK, France etc., each have safety codes for hydrogen above ground that will need integrating with subsurface safety. Thus far, demonstration projects have proceeded under existing frameworks by classifying hydrogen similarly to natural gas in terms of risk category, and additional precautions were voluntarily taken (Louie and Ehrhart 2024a) .

Case Studies of Underground Hydrogen Storage in Europe

Europe is at the forefront of developing real-world projects to demonstrate and scale underground hydrogen storage. This section reviews several existing and proposed UHS projects across Europe, highlighting different storage types and lessons learned.

1. HyPSTER (France) – Salt Cavern Hydrogen Storage Demonstrator (Djizanne et al. 2022)

One of the milestone projects in Europe is **HyPSTER (Hydrogen Pilot STorage for large Ecosystem Replication)** in Etrez, France. HyPSTER is the EU's first supported pilot of green hydrogen storage in a salt cavern:

- **Project Overview:** Launched in 2021, HyPSTER aims to showcase the entire value chain: renewable hydrogen production via electrolysis, storage in a salt cavern, and withdrawal to supply industry and mobility uses. It is co-funded by the European Clean Hydrogen Partnership.

- **Storage Site:** Etrez is a natural gas storage site operated by Storengy (an ENGIE subsidiary) with multiple salt caverns in bedded salt formations. Cavern "EZ53" was selected for conversion to hydrogen. This cavern has an approximate capacity of *about 50 tonnes of* H_2 (which is ~1,600 MWh of energy). By comparison, 50 tonnes could fuel 2,000 buses for a day.

- **Timeline:** The first hydrogen was injected in mid-2023, and by September 2023 the project was officially inaugurated with dignitaries attending. The plan is to gradually scale up hydrogen injection to reach the cavern's full capacity by 2026.
- **Operations:** Hydrogen is generated on-site from renewable electricity (a 1 MW electrolyzer) and stored at pressures up to ~200 bar in the cavern. During the pilot phase, various cycles will test injection/withdrawal and monitor any changes in cavern behavior or gas quality. Initial results have been positive – Storengy reported that the cavern and facilities functioned as expected with hydrogen, with no safety issues or integrity problems.

- **Significance:** HyPSTER adds an essential piece to France's "Zero Emission Valley" initiative in Auvergne-Rhône-Alpes, by providing storage to buffer hydrogen supply for local hydrogen refueling stations and industries. It also provides data to replicate salt cavern storage at other European sites. The project demonstrates technical feasibility and helps develop operational protocols for H_2 in salt caverns. Because Storengy runs many natural gas caverns, a successful HyPSTER pilot could pave the way to converting or building caverns for hydrogen across France and Europe.

2. Underground Sun Storage (Austria) – Porous Reservoir Pilot (Pichler 2019)

Austria's **Underground Sun Storage (USS)** project is a groundbreaking demonstration of hydrogen storage in a depleted gas reservoir:

- **Project Description:** Run by RAG Austria AG (the main gas storage operator in Austria), USS is the *world's first* project to store *100% hydrogen in a porous underground reservoir*. The project began in 2017 and in April 2023 it entered the operational phase.
- **Storage Site:** A small depleted natural gas field in *Gampern, Upper Austria* (sometimes referred to as Pilsbach/Rüdersdorf site) was selected. This reservoir is about 1,000 m deep and had a known trap and seal. The scale is pilot/demonstration: about 4.2 GWh (15 million MJ) of energy in hydrogen was planned to be stored, corresponding to roughly 100 tonnes of H_2 (if 4.2 GWh_e, or ~1,260 MWh_th, it might be a mix, but the press release says 4.2 million kWh which is 4.2 GWh) .
  Technical Insights: USS monitored for issues like hydrogen loss or methane generation. While detailed results are not all public yet, RAG indicated that the project met its goals and provides a template for larger projects. The reservoir's performance in terms of deliverability and containment was as expected, and the entire "solar-to-hydrogen-to-gas storage-to-electricity" chain was demonstrated.

- **Importance for Austria and Europe:** Austria has significant underground gas storage infrastructure (large porous storages used for natural gas trading in Central Europe). With this project, RAG showed that these storages can gradually transition to storing renewable energy. They note Austria's ideal geology and existing capacity could be repositioned as part of the future hydrogen system. On a European scale, it's a proof-of-concept that any region with gas fields can utilize them for hydrogen, not just salt-rich regions. RAG has already embarked on a follow-up project "Underground Sun Storage 2030" to scale up the concept to a larger field and address longer-term issues.

3. Aldbrough Hydrogen Storage (UK) – Large-Scale Salt Cavern Conversion (Evans et al. 2021)

The **Aldbrough** site in East Yorkshire, England, exemplifies a forward-looking project integrating hydrogen storage into a broader hydrogen cluster:

- **Background:** Aldbrough is currently a natural gas storage facility (commissioned 2011) with nine salt caverns, jointly owned by SSE Gas Storage and Equinor. These caverns (each enormous, "the size of St. Paul's Cathedral") are used for high-deliverability gas storage.

- **Hydrogen Plan:** In 2021, SSE Thermal and Equinor announced plans to develop **one of the world's largest hydrogen storage facilities** by converting part or all of the Aldbrough caverns to hydrogen service. The project is targeting an **initial capacity of at least 320 GWh** of hydrogen storage by around 2028. For perspective, 320 GWh (energy) is roughly 8,000 tonnes of hydrogen – a massive scale that reflects the ambition to support an entire regional hydrogen economy.

- **Integration with Hydrogen Ecosystem:** The stored hydrogen would come from both **blue hydrogen** (from natural gas with CCS) and **green hydrogen** (from offshore wind power) produced in the Humber region. Equinor is developing 0.6 GW (later 1.8 GW) of blue hydrogen at Saltend and SSE/Equinor plan a hydrogen power plant at Keadby. Aldbrough storage will ensure these production facilities can run at high capacity even when demand is low, and supply hydrogen for a variety of uses including power generation, industrial fuel switching, and transport fuel in that region.

- **Status and Future:** As of the last update, the project was in engineering design and seeking regulatory/business model clarity (final investment decision will depend on government support and hydrogen market development). The UK government has shown support, naming it in strategies and offering funding for front-end engineering design (FEED). If it proceeds, by late 2020s Aldbrough could be a cornerstone of the UK's hydrogen infrastructure, showcasing salt cavern conversion at scale. It's notable that initial use might be **cavern repurposing** (perhaps starting with one cavern for a smaller "Pathfinder" project of ~20 GWh as per some sources, then expanding). Over time, more caverns or newly leached caverns could bring capacity well beyond 320 GWh.

- **Significance:** Aldbrough highlights how existing fossil fuel infrastructure (designed for natural gas) can be leveraged and expanded for hydrogen. It also underscores the "cluster" approach: connecting production, storage, and consumption in one geographic zone (the Humber industrial cluster) for maximum efficiency. If successful, it will be a model for other clusters (e.g. in the North Sea basin or elsewhere in Europe) to follow.

4. ACU (Advanced Clean Energy Storage) – Lessons from Outside Europe

While focusing on Europe, it's worth briefly noting that the world's largest planned hydrogen storage project is in the USA (Utah), the Advanced Clean Energy Storage (ACES) project, which will use salt caverns to store green hydrogen to feed a 840 MW hydrogen-capable gas turbine plant. ACES is creating two huge caverns in a salt dome with a storage capacity of around 150 GWh each (Satyapal et al. 2007) . The project kicked off injections in 2022/23 and plans full operation mid-decade. This shows that large salt cavern storage is not just theory – it's being built at grid scale. Europe's salt cavern projects (like Aldbrough) are of a similar nature. Additionally, in the US Gulf

Coast, hydrogen has been stored for industrial use for years in salt caverns (ConocoPhillips Clemens dome in Texas, etc.) albeit for non-grid purposes. Those caverns (with ~95% H_2 mixtures) confirm the long-term stability of salt cavern H_2 storage; one site in Texas has stored hydrogen for refinery feedstock for decades (Law et al. 2013) .

5. Other European Initiatives:

- **Gasunie HyStock (Netherlands) (Kooten 2025):** Gasunie's subsidiary EnergyStock performed successful hydrogen injection tests at Zuidwending salt cavern site starting in 2021 . A pilot in one of the caverns demonstrated that "the current way of storing natural gas is also suitable for hydrogen" and hydrogen can be stored and withdrawn in a controlled, safe manner . Now Gasunie is developing a plan to outfit four caverns for hydrogen by 2026-2027, offering an open-access storage service for the Dutch market . This will integrate with the Netherlands' Hydrogen Backbone.
- **Storengy Projects in Germany and UK (Berest et al. 2021; Evans et al. 2021):** Storengy (ENGIE) is examining its gas caverns in Germany (e.g. in Saxony-Anhalt) for hydrogen conversion. In the UK, Islandmagee in Northern Ireland (seven planned caverns) was initially for natural gas, but its developers have proposed shifting to hydrogen storage given NI's renewable plans. These are in early stages.
- **RAG Storage in Germany (Xie et al. 2023):** The HyStorIES project identified a number of potential aquifer and gas field sites across Europe for future development. In Germany, one example in literature is a concept to use the *Etzel caverns* (major gas storage in northern Germany) for hydrogen blending or storage – RWE and Uniper have looked at this. Another is the *Ketzin* structure (the former CO_2 storage pilot site near Berlin) which some researchers considered for hydrogen test since it held town gas historically.

Figure 10 location of RAGS storage area

- **Spain (H2STORE) (Marco De Lucia 2025):** Spain has salt formations (for example in Catalonia and southern Spain). A project called H2STORE, under the EU HyUnder initiative, assessed potential caverns in Spain. While no field project has started yet, Spain's hydrogen strategy includes geological storage as a mid-term objective to manage its expected solar surplus.

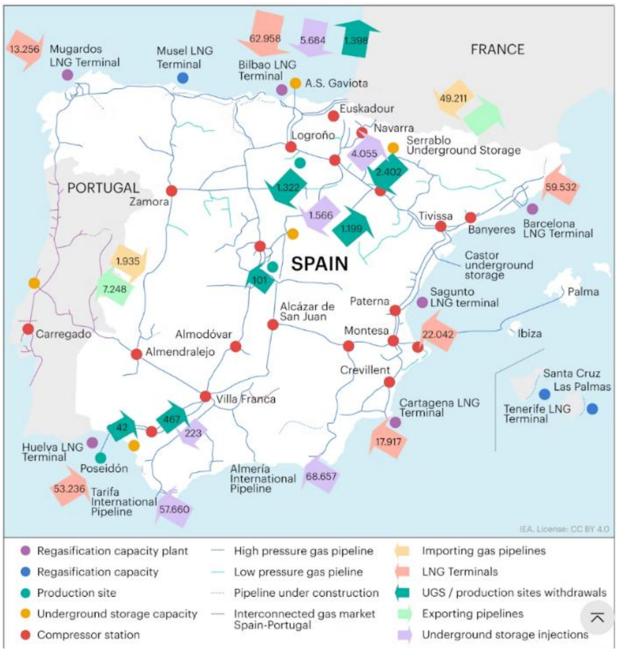

Figure 11 Spain's natural gas infrastructure (International Energy Agency (IEA) 2022)

Each of these efforts contributes to a body of knowledge and confidence. They also help identify best practices and necessary regulatory adjustments. For instance, HyPSTER and similar EU-backed projects often publish results that feed into standards (such as how to measure hydrogen leakage, or how to model cavern thermodynamics with hydrogen, etc.). Already, these case studies have yielded some general conclusions(Febbo et al. 2025; Kondziella et al. 2023; Moore and Shabani 2016; Slabon 2025):

- **Hydrogen storage in salt caverns is achievable using existing solution-mined caverns with minimal modifications** – as evidenced by HyPSTER, Gasunie, and Texas experience. It mainly requires ensuring surface and well materials are compatible.
- **Porous reservoir storage of hydrogen is proven at pilot scale** – as shown by RAG's project, with performance aligning with predictions (no major loss, successful withdrawal).

- **Integration with renewables and end-use is key** – most projects are not just storing for storage's sake but linking storage to a local hydrogen loop (be it a power plant or industrial cluster). This integrated approach is likely to be the template going forward.

The forthcoming Gas and Hydrogen Package (Louie and Ehrhart 2024b): In 2021, the European Commission proposed amendments to gas market legislation to incorporate hydrogen. This includes a draft Hydrogen and Decarbonised Gas Market Regulation and Directive. These proposals aim to create the regulatory frameworks for hydrogen networks and potentially storage. For example, they propose rules for third-party access to hydrogen networks and want to repurpose existing gas infrastructure where possible. However, specifics on storage are limited; they generally carry over principles from gas storage (like non-discriminatory access if storage is regulated).

- **TEN-E Regulation and PCI**: The Trans-European Networks for Energy regulation was revised to include hydrogen infrastructure as eligible for Projects of Common Interest (PCI) status. Storage projects can thus potentially get PCI designation, speeding permitting and access to EU funds. In 2021, some hydrogen storage initiatives (like HyStorIES) were funded under Horizon and the Clean Hydrogen JU (Kondziella et al. 2023).

- **Clean Hydrogen Partnership and Funding**: The EU's R&D funding (Horizon Europe) is backing research on UHS (e.g., Hystories project, HyUSPRe project) to close knowledge gaps by 2025, which will inform regulation.

A key development is industry and expert recommendations for explicit targets and support. Gas Infrastructure Europe (GIE), which represents European gas storage operators, has been vocal. Their 2023 report suggests the EU should set a 2030 UHS capacity target of 5 million m³ hydrogen (≈45 TWh LHV) and incorporate that into planning scenarios (Bonciu 2022; Famà 2024) . They argue that "the market alone will fail to close the gap" between what's needed and what will be built under current conditions. They propose EU-level coordination such as:

- Recognizing hydrogen storage as critical infrastructure in the EU energy policy (just like gas storage is recognized under security of supply regulations).

- Possibly establishing support mechanisms like contracts for difference for hydrogen storage or capacity payments.

- Streamlining permitting processes across member states for UHS, as current procedures can be lengthy and uncertain, which deters investment.

As of 2025, no EU law specifically mandates hydrogen storage build-out or creates a dedicated subsidy. But the conversation is ongoing. The REPowerEU plan (2022) (Bonciu 2022) highlighted the need to accelerate hydrogen infrastructure by 2030 (mainly production and import terminals, but implicitly storage too, as it speaks of developing "the hydrogen economy").

2. National Regulatory Developments:

Different European countries are moving at varied speeds:

- **Germany:** Germany's gas storage operators (e.g., Uniper, VNG) are exploring hydrogen. The German government updated its Energy Industry Act to allow hydrogen networks (as a separate asset class from natural gas). While pure hydrogen storage is not yet regulated, discussions are on whether it should be part of regulated network operations or a competitive activity. Germany's Hydrogen Strategy (2020) mentions geological storage as a necessity for large-scale hydrogen by the 2030s. The mining authority in Saxony-Anhalt approved in 2022 a test to store hydrogen in a cavern (bad Lauchstädt Energy Park project). German law still requires case-by-case approval for hydrogen in storages that were for gas (Neumann and Zachmann 2008).

- **UK:** The UK is developing business models for low-carbon hydrogen via government support (contracts). For hydrogen storage, the UK government initiated a "Hydrogen Storage Business Model" consultation in 2022. They acknowledged that large-scale hydrogen storage may need similar treatment to gas storage (or power capacity) to incentivize it. In the interim, they provided some grant funding (e.g., for Aldbrough FEED studies, and for offshore storage studies). Regulatory wise, UK's HSE (safety executive) is engaged to ensure safety at sites like Aldbrough. The existing UK gas storage licensing can technically cover hydrogen, but specifics (like how to measure energy content, how to ensure purity if blending, etc.) are being worked out (Evans et al. 2021; Harati et al. 2024).

- **Netherlands:** The Dutch government strongly supports hydrogen and is planning a national hydrogen network by 2027. Gasunie (state-owned gas TSO) is tasked with converting pipelines and is also behind HyStock storage. Regulatory changes allowed existing gas storage licenses to be used for hydrogen pilot (as was done for HyStock). Likely, hydrogen storage will become a regulated asset under Gasunie if considered part of network operation for strategic storage or could be competitive if multiple parties want to store (that is still being determined). The Dutch Mining Act will need tweaks to explicitly mention hydrogen storage; this is underway.

- **France:** Storengy's projects like HyPSTER (Moret 2022) proceeded under existing mining code rules for gas storage, with special permissions. France's Multi-Annual Energy Plan (PPE) calls for exploring hydrogen including storage. The regulator (CRE) and government will likely integrate hydrogen storage in their gas storage regime if needed to ensure security of supply. Currently, France mandates gas storage filling for winter; a future scenario might similarly treat hydrogen storage as strategic (especially if hydrogen is used for heating or electricity in winter) (Storengy, Energy, and Auvergne-Rhone-Alpes 2022) .

- **Spain and Others:** Spain and Portugal's strategies foresee 40+ GW of electrolyzers by 2030 and implicitly large storage (Simon, Férriz, and Correas 2015). However, regulatory frameworks are nascent. They might follow an EU-level direction or treat it case-by-case. Eastern European countries (Poland, Romania, etc.) with salt caverns are interested but awaiting clearer EU signals (Iordache et al. 2014; Uliasz-Misiak et al. 2022).

3. Key Regulatory Challenges:

- **Classification and Definitions:** Is hydrogen storage considered a gas storage (and thus maybe regulated similarly to natural gas storage), or is it a new category? How to classify stores that might switch from methane to H_2 (transitional regulation, as initially it could be blends)? Some countries might need to amend laws to explicitly list hydrogen as a commodity that can be stored underground (Kondziella et al. 2023).

- **Third-Party Access vs Proprietary Use:** In natural gas in Europe, many storages are required to offer third-party access (TPA) unless exempt, to promote competition. For hydrogen, early projects are often integrated (the operator of storage also produces/uses the H_2). Requiring TPA too early might discourage development because an investor might want to ensure their own use. The EU Gas Package proposals indicate that pure hydrogen infrastructure could initially be exempt from TPA until a market forms. Over time, if a hydrogen trading market emerges, storages might need to offer services to any supplier (like gas storages do via auctions or regulated tariffs) (Boon et al. 2024).

- **Regulatory support and incentives:** As mentioned, without some form of intervention, the first large hydrogen storages may not be financially viable given high upfront costs and uncertain utilization. Regulatory bodies are discussing mechanisms. For example, one idea is a capability payment: paying storage operators for maintained deliverability capacity (like a strategic reserve payment). Another is including hydrogen storage in Capacity Mechanisms (like how power plants get paid for capacity) (Guduru et al. 2025) .

- **Administrative Procedures:** Currently, developing a new storage (especially a cavern) can take many years for permits (environmental impact assessments, mining permits, water use permits, etc.). Streamlining these processes is a priority identified by industry. The EU could help by issuing guidance or by making hydrogen storage projects eligible for simplified permitting under energy infrastructure laws. Some nations might designate certain UHS projects as "national interest" to fast-track them (Bulat, Kaymakçı, and Ilhan 2025; Jaarsma et al. 2024).

- **Safety and Standards:** Regulators need to set standards for acceptable leakage rates, monitoring requirements, etc. Many technical standards from natural gas storage (e.g., for well integrity) apply, but some new ones may be needed for hydrogen (for instance, material standards for hydrogen service). This is underway in bodies like ISO and CEN – developing hydrogen-specific standards. Having clear safety standards will ease regulatory approvals by providing checklists for project developers and reviewers (Bulat et al. 2025; Rigas 2024).

4. Recent Policy Initiatives and Industry Roadmaps:

- **Hydrogen Storage Roadmap** (Guduru et al. 2025; Pinto 2024) . They call for urgent action: clear EU strategy focusing on UHS, funding support for pilots, inclusion in National Energy & Climate Plans, and establishing a regulatory sandbox for early projects (to experiment with market rules in a controlled way). They highlight that without a "Hydrogen Storage Strategy," investments might lag and jeopardize hydrogen adoption.

- **National Hydrogen Plans:** Many countries (Germany, France, Netherlands, UK, Spain, Italy, etc.) have hydrogen strategies or roadmaps. These documents

vary in detail on storage (Kukkonen 2024; Pichler 2019).
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- **EU Security of Supply Considerations (Blanchard 2024):** The 2022 energy crisis (due to Ukraine war) refocused EU attention on gas storage – EU passed a regulation requiring member states to fill gas storages to certain levels pre-winter. Now looking longer term with hydrogen, the EU may consider something analogous: ensuring a baseline of hydrogen storage once hydrogen becomes integrated in energy supply. This would be more relevant post-2030 when hydrogen might fuel significant heating or power generation (Evans et al. 2021).

Potential Underground Hydrogen Storage Sites in Greece: Geological Assessment and Prospects

Greece, while not a traditional hub for underground gas storage due to limited domestic gas production, has been exploring its subsurface potential for energy storage, including hydrogen. Given its geography (numerous sedimentary basins, but relatively few large known gas fields or extensive salt domes), identifying suitable sites requires detailed geological scrutiny. Recent studies by Greek researchers and institutions provide insight into where hydrogen might be stored underground in Greece, and what capacity could be achieved (Arvanitis et al. 2020, Bellas et al., 2023).

Geological Context: Greece's geology is complex, featuring folded mountain belts and basins associated with the Alpine orogeny. Potential storage formations include:

- **Sedimentary Basins**: e.g. the Mesohellenic Trough (NW Greece), Thessaloniki Basin (northern Greece), various basins in western Greece, which contain porous sandstones and conglomerates (Arvanitis et al. 2020).

- **Evaporite (Salt) Deposits**: Greece has some evaporitic formations, though not as massive as those in N. Europe. Notably, bedded salts or salt-rich sequences exist in *western Greece* (associated with the and Ionian zone e.g. Kamperis et al., 2022; Bellas et al., 2023; Soto et al., 2024) and in *Crete* (Manakos & Vidakis, 2000).

- **Depleted Hydrocarbon Fields**: Small oil and gas fields have been developed in Greece – primarily the offshore *Prinos* oil and gas field (HEREMA, 2026) and the offshore *South Kavala* gas field (HDARF, 2021) in the North Aegean Sea, plus very small onshore gas at *Epanomi* (Thessaloniki area- not exploited) and the undeveloped *Katakolo* offshore oil/gas structure in Western Greece (Makri et al., 2021) .

A comprehensive 2020 study by Arvanitis et al. (published in *Energies*) evaluated multiple underground storage options in Greece, including natural gas, hydrogen, thermal, and CO_2 storage. From that and related research, the following key candidate sites for **hydrogen storage** emerge:

- **Salt Cavern Candidates – Ionian Islands (Corfu and Kefalonia)** (IENE, 2015)**:** Geological data indicates the presence of significant evaporite (salt) formations in the subsurface of the Ionian Islands, particularly Corfu and Kefalonia . These evaporites are part of the Ionian zone sequence and could potentially be solution-mined to create caverns. Arvanitis et al. identify Corfu and Kefalonia as promising sites for underground hydrogen storage, with salt caverns being the preferred method. They note that salt/evaporite caverns allow much higher hydrogen injection and withdrawal rates compared to porous formations, making them ideal.

To quantify potential: the study modeled a “capsule-shaped” cavern (60 m diameter, 300 m tall) at ~650 m depth in an evaporite formation. Using conservative assumptions (working gas volume ~367,000 m³ H_2) they calculated an energy storage capacity of ~80 GWh_th, which is ~26.6 GWh_e, per cavern for the sites considered (Arvanitis et al. 2020) . For Corfu and Kefalonia, this suggests each island could host at least one such cavern. Indeed, they concluded that Corfu and Kefalonia together could store about 53,200 MWh_e (53.2 GWh_e), which could supply the electricity needs of 6,770 households in the Ionian islands. This scenario is based on a single cavern in each; there may be room for more depending on the lateral extent of the salt deposits.

The evaporite in question likely corresponds to Triassic sequences known in the region (Bellas et al., 2023). These salt layers might not be very thick in all places, so site-specific geological surveying (seismic, exploratory drilling) would be needed to confirm cavern feasibility (thickness >100 m, depth 500–1500 m ideal, and minimal faulting). If confirmed, salt caverns in Greece would mark a significant expansion of Europe’s salt cavern storage map into SE Europe.

In addition to the previous a new candidate Site of Triassic evaporites located on Zakynthos island is going to be presented (as an example) in the Deliverable 4.3 (at the boundary of Ionian and Pre-Apulian geotectonic zones, Bellas et al., 2023). The site study will include data from various sources as publicly available seismic lines, geological maps and detailed stratigraphic columns from the surrounding area.

- **Salt Cavern Candidate – Heraklion, Crete.** The same Greek study (Arvanitis et al.) mentions evaporite formations near Heraklion in Crete as suitable for underground gas storage (and by extension possibly hydrogen). Crete’s Heraklion basin has thick Messinian evaporites (from the late Miocene salinity crisis). These salts have been considered in the past for hydrocarbon trapping and potentially for storage. The authors also note Heraklion evaporites are good for gas storage, though their focus was on natural gas in that context. A salt cavern in Crete could theoretically store either natural gas or hydrogen. However, Crete’s energy system is isolated (not completely grid-connected to mainland until recently partial interconnections), so a hydrogen cavern there could help store surplus solar/wind from the island’s growing renewables, then supply power when needed. The feasibility would depend on cavern development cost and the local energy economics. If Crete pursues a green hydrogen economy (it has huge solar potential and develops a Hydrogen Valley as well, see Crave H2), a cavern could help balance the island's grid.

- **Depleted Gas Field – South Kavala (HRADF 2021):** South Kavala is a depleted offshore natural gas field in the Gulf of Kavala (Northern Aegean). It is consisted by a porous limestone reservoir at ~1700 m depth. Greece has decided to convert South Kavala into the country's first Underground Gas Storage (UGS) site for natural gas, to enhance security of supply. The capacity is modest (roughly 0.7-1 bcm of natural gas, ~7 TWh) but important regionally. Once it becomes operational as a gas storage, the question arises: could it later store hydrogen or blends? South Kavala's operator could also consider storing *hydrogen-natural gas mixtures* in the future when hydrogen becomes available. Pure hydrogen storage might be further off due to pipeline and user constraints (the current goal is to use it for NG). However, it sets a precedent – the licensing, regulatory framework, and technical know-how gained from South Kavala UGS can transition to hydrogen. Additionally, Arvanitis et al. noted that Prinos and South Kavala gas fields combined have significant energy storage potential in terms of MWh if used for methane. The Prinos field (oil with gas cap) is still in production, so not immediately available, but South Kavala was ideal due to depletion. Recent developments point rather to CO2 storage in Prinos e.g. EnEarth, 2026 (see also below).

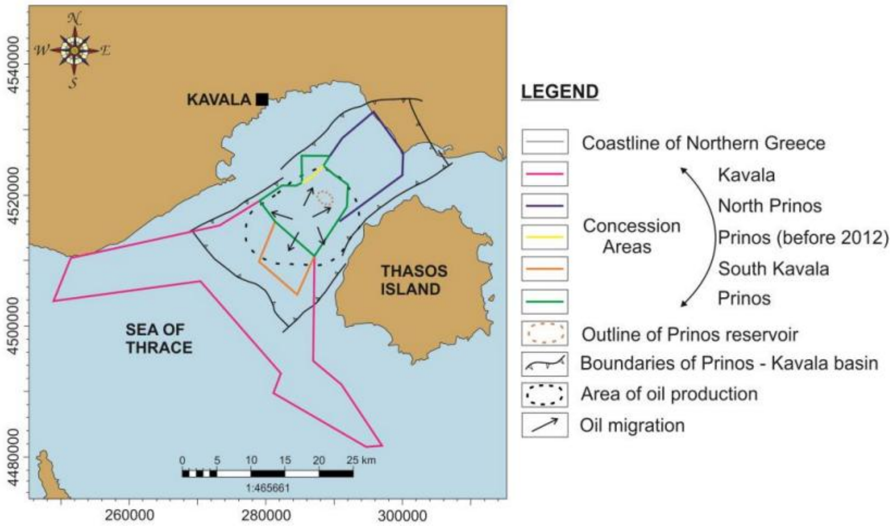

Figure 12 Geologic sketch map of the Prinos–Kavala sedimentary basin in the northern Aegean Sea showing the distribution of oil and gas resources (Koukouzas and Tasianas 2016).

- **Depleted Field, Prinos (Avraam and Vatalis 2023; Proedrou and Sidiropoulos 1992):** Prinos oil field, adjacent to South Kavala, still produces oil and associated gas (some of which is reinjected). If/when Prinos is depleted and abandoned for oil, its reservoir might be repurposed. It's larger than South Kavala, so could potentially store more gas. One challenge: being an oil reservoir, it has residual oil which hydrogen could potentially react with (though likely minimal reaction). More likely is that Prinos might be used for CO_2 storage (as MOE has considered for Enhanced Oil Recovery with CO_2), but hydrogen storage is conceptually possible much later. Recently the project of repurposing of prinos has started and as it is planned there will be up to 2,8 MtCO2 per year capacity (EnEarth, 2026, EU funding & tenders Portal: project ongoing, CEF).

- **Onshore Depleted Fields or Aquifers, West Greece (Trifos, Achira in Aitoloakarnania) (Arvanitis et al. 2020):** The Arvanitis study identifies **Trifos and Achira** in the Aitoloakarnania region (Central-Western Greece) as promising sites for hydrogen storage in porous media . These sites correspond to areas with onshore wind farms (hence existing energy projects) and likely have suitable geology underground. They may be deep sedimentary formations (possibly aquifers or low-yield gas accumulations) that could serve as traps. The idea is to pair local wind power with hydrogen production and storage. Indeed, the study mentions those locations already produce onshore wind power, whose excess could generate hydrogen to be stored underground.

  The modeling in the study assumed the same capsule-shaped cavern scenario for Trifos and Achira as for the salt sites, implying they envisioned solution mining an evaporite there. But Trifos and Achira are not known salt sites; likely they intended a generic case. More likely, those sites would entail porous reservoir storage (either a depleted small gas reservoir or an aquifer). The conclusions indicate each could also store ~26.6 GWh if a cavern were possible, but if not salt, the capacity in a porous setting could differ. It's possible there are minor evaporitic layers in Western Greece (there are some salt springs etc, hinting at subsurface salt). Alternatively, the authors might have proposed engineered caverns in hard rock (less likely). Regardless, Trifos and Achira stand out as candidates for a pilot project in Greece, given the co-location with renewables and presumably favorable geology.

  One of the examples used in our current study refers to a evaporite/salt site located in western central Greece that we purpose (following leaching) for hydrogen storage in a cavern. Again the study includes and synthesizes data from various sources as publicly available seismic lines, geological maps and detailed stratigraphic columns from the surrounding area (more details in Deliverable 4.3).

- **Deep Saline Aquifers – Mesohellenic Trough & Thessaly (Vamvaka et al. 2006):** The Mesohellenic Trough in NW Greece is a large Cenozoic basin with thick sequences of sandstones and conglomerates, some of which are aquifers. It's been studied for CO_2 storage and geothermal but also flagged for gas storage potential. The Western Thessaloniki basin (around Axios delta) is another area containing deep aquifers. Arvanitis et al. found these had the highest potential for underground gas storage among studied aquifers. These could be targets for hydrogen storage in aquifer structures if detailed analysis provides for good traps and seals. For instance, a closed anticline filled with brine could theoretically be turned into a hydrogen reservoir.

  A specific example: the study identified some aquifers in Western Macedonia/Thessaly that could cover significant energy needs if used for storage. For hydrogen, they did not explicitly calculate aquifer capacities (focus was more on heat and methane), but the presence of sizeable porous rock volumes is promising. One can imagine that after 2030, if Greece has surplus solar or wind power, using a deep aquifer in, say, the Amyntaio or Ptolemaida region (where lignite mines and power plants operated the past decades) for hydrogen storage could help repurpose those energy regions.

Challenges for Greece's UHS (Arvanitis et al. 2020; Avraam and Vatalis 2023):

- Geological uncertainty: Compared to Northern Europe, Greece's suitable formations are fewer and rather smaller. Extensive analysis is needed to ensure any chosen site can hold hydrogen effectively. For salt cavern creation, water availability and brine disposal –environmental aspects- must be seriously considered (particularly on islands like Corfu/Kefalonia – brine could be potentially released to sea with care).

- Scale: The potential capacities discussed (tens of GWh) are on the smaller side relative to Europe's needs. Greece might not need hundreds of TWh internally, but if aiming to export hydrogen or cover seasonal swings, it will need multiple sites and technologies. We should also have in mind, that particularly during summer period, the amount of population in Greece, mosty in the islands, increases dramatically due to tourism and the necessity for energy demand takes on almost exponentially. Moreover, Greece could act as a regional hub, transferring energy to the neighboring countries, such as Bulgaria, Romania and Albania.

- Infrastructure: Hydrogen pipelines or transport links from production sites to storage and then to demand centers will need development. For instance, if hydrogen is made by offshore wind in the Aegean in the future, how to get it to a storage in NW Greece? Although a major pipeline route exists (TAP, compare deliverable 4.3) this is completely devoted to NG for the moment. Plans should include gas mixtures and pipelines materials should permit such transportation without any security and safety matters.

- Regulation and investment: As a first mover in its region, Greece may have to adapt its mining and energy regs (like others, it will likely treat hydrogen under existing framework until updated). Funding of pilot projects (including EU projects and/or State support) will be important since private sector might be hesitant without proven results. There is already a recent legislation governing the hydrogen transportation, but nothing on the subsurface storage of H2 and/or the exploration of natural H2.

Outlook for Greece's Hydrogen Storage:

Greece's location could allow it to be a renewable energy hub (solar, wind, possibly imports from North Africa) and thus hydrogen producer (Labos 2025). Having domestic storage will increase the flexibility and security of its hydrogen supply. Additionally, Greece could provide seasonal storage services to its neighbors in Southeast Europe if interconnections exist (like storing summer excess from Balkans and supplying in winter; akin to how Ukraine and Austria do for natural gas in Europe).

In summary, from the literature studies so far, the most promising near-term UHS sites in Greece are:

- **Corfu and Kefalonia:** for salt cavern development, collectively offering on the order of 50 GWh_e storage with two caverns.

- **Western Greece (Aitoloakarnania):** areas like Trifos/Achira where wind farms exist and subsurface geology may allow either a mined cavern or a closed aquifer structure, for tens of GWh scale .

- **South Kavala (offshore):** once converted to gas storage, possibly a site for future hydrogen blend or pure H_2 storage given suitable metallurgy and cleansing of residual gas
- **Heraklion (Crete):** a candidate if a strategic need arises for Crete's grid and the Hydrogen Valley is realized – EU Clean Hydrogen Partnership project: Crave H2 (could also be used for natural gas or hydrogen).

- **Other sedimentary traps:** e.g. deep parts of Mesohellenic Trough, or smaller onshore structures that were explored for oil (some had gas shows but were non-commercial) – those could be repurposed.

Greek research is ongoing; more data (e.g., well logs, core analyses) is being compiled by HSGME. Encouragingly, preliminary results are positive – calculations show that even a small country like Greece could utilize underground hydrogen storage to cover regional energy needs, such as supplying thousands of households with electricity from stored hydrogen. As Greece pursues climate targets and energy security, developing these UHS options can be a strategic move, complementing other storage (like batteries or pumped hydro) to ensure a reliable and green energy system.

Challenges and Future Outlook

As Europe advances toward a hydrogen-powered future, underground hydrogen storage will play an increasingly pivotal role. However, several challenges must be addressed to unlock its full potential, and the landscape of UHS will evolve with technological progress and policy support. In this final section, we discuss overarching challenges and the outlook for UHS in the coming decades:

Key Challenges:

- **Technology Maturation:** While analogous to natural gas storage, UHS is still an emerging technology. More pilot projects and research are needed to fully understand long-term effects. Questions like *"How will a reservoir perform after 20 cycles of hydrogen?"* or *"What is the optimal cushion gas strategy for each scenario?"* require empirical data. Issues like material embrittlement or microbial effects are known qualitatively, but robust engineering solutions (special steel alloys, reservoir treatment methods) are in development (Atinkut 2025). The challenge is to reach a point where building a hydrogen storage in the subsurface is almost as routine as a gas storage. This will likely happen through the 2020s with accumulating experience from projects like HyPSTER, RAG's Sun Storage, Aldbrough, etc., and perhaps new demos in various geologies (salt, aquifer, etc.) (Uliasz-Misiak et al. 2022).

- **Scaling Up Capacity:** Europe's hydrogen storage needs could be very high if hydrogen is to replace natural gas at scale. Models suggest on the order of 45 TWh by 2030 and ~300 TWh by 2050 for the EU to cost-optimally achieve climate targets. The current operational or planned projects are in the tens of GWh at most – a tiny fraction. The challenge is scaling by orders of magnitude within 1-2 decades. This means moving from single pilot caverns to clusters of caverns, from small fields to major geological formations. It entails substantial investment and coordination (Kondziella et al. 2023). For perspective, converting just 10% of Europe's existing natural gas storage capacity to hydrogen (assuming similar volumetric capacity) would yield on the order of 50–100 TWh of hydrogen storage. So repurposing current storages (with modifications) could cover a chunk, but new storages will also be needed (especially in regions currently without any gas storage, like many renewable-rich southern areas) (Kukkonen 2024).

- **Infrastructure Integration:** Storage doesn't exist in isolation – it must connect to hydrogen production and demand. Building hydrogen pipelines or trucking hydrogen to/from storage is non-trivial. Some salt cavern sites (e.g. in UK or DE) are conveniently near industrial clusters, but others might be remote. Planning the hydrogen infrastructure (the "Hydrogen Backbone" pipelines across Europe) will need to incorporate storage nodes (Evans et al. 2021; Harati et al. 2024). For example, a European backbone might deliberately route through areas with good storage geology (like via North Germany salt dome region, the Paris Basin, North Sea fields, etc.). At the distribution level, if hydrogen is used for heating in some countries, then regional storages will tie into distribution grids. The challenge is coordinating all this so storage capacity is effectively utilized (Alms et al. 2023).

- **Market Uncertainty and Investment Risk:** As highlighted in the regulatory discussion, right now there is no established market price for hydrogen storage services. Investors face uncertainty on revenue streams. It's challenging to invest hundreds of millions in a salt cavern that might only be used when there's excess renewable power (which in early years might be sporadic) (Kondziella et al. 2023). There's a risk of a valley of death for projects if policy doesn't de-risk them. Overcoming this requires interim government support or guarantees (e.g., making hydrogen storage part of strategic energy infrastructure with regulated returns or capacity contracts). The timeline to get these in place is short if 2030 targets are to be met (Blanchard 2024).

- **Cross-border Coordination:** Energy storage (like electricity grids) often has transnational benefits. One country's storage can help neighbors (e.g. German wind power stored in Danish caverns, or Spanish solar stored in French aquifers, hypothetically). Ensuring open access and fair cross-border utilization of hydrogen storage will be a challenge, given national tendencies to secure their own energy supply (Pichler 2019). The EU likely will encourage a network approach where hydrogen storage is considered a European asset as much as national. This is analogous to how gas storages in certain countries provide EU-wide energy security (Austria, for instance, stores gas for others). Developing interconnectors and agreements for hydrogen flows will maximize usage of best geological sites regardless of location (Qian et al. 2025).

- **Public Perception and Environmental Monitoring:** While, as discussed, UHS is environmentally low-impact, local communities may have concerns about any subsurface operations, especially novel ones. Gaining public acceptance requires transparency, stringent safety assurance, and showing community benefits (like local jobs or community energy schemes) (Kaczmarek and Blachowski 2025). Continuous environmental monitoring (groundwater quality, induced seismicity) at storage sites will be important to demonstrate safe operations. One advantage in Europe is many storages will be at existing industrial or storage sites, minimizing new disturbances (Tarkowski and Uliasz-Misiak 2025a).

- **Competition with Alternatives:** Hydrogen is one way to store energy; there are others (batteries, pumped hydro, emerging options like liquid air storage). For short-term fluctuations, batteries or demand response might be more cost-effective. There could be a tendency to rely on those and under-invest in hydrogen storage until it's almost too late for seasonal needs. Making the case that *some* storage must be in the form of hydrogen for multi-month buffering is crucial (Tarkowski 2019). Additionally, some propose converting hydrogen to other carriers for storage (like ammonia storage in tanks or converting to synthetic methane and storing in existing gas storages). These have their own pros/cons. UHS directly storing hydrogen is generally more efficient (each conversion costs energy), but if hydrogen proves tricky, some might push for methanation + use existing methane storage. The future will tell if hydrogen purity is maintained or if blending and conversion become more widespread as a workaround. However, given the EU's direction to use hydrogen directly in many cases, UHS remains a priority (Ugarte and Salehi 2022).

Looking ahead to the 2030 horizon:

We can expect the first wave of commercial UHS facilities to be up and running. These include projects like Aldbrough (UK) and likely similar large caverns in Germany or the Netherlands, and perhaps a couple of larger porous storages (maybe in the North Sea area or Austria/Germany) (Atinkut 2025; Slabon 2025; Xie et al. 2023). In the interim, some natural gas storages might start to accept blended hydrogen (e.g. 5-10% hydrogen mixed with natural gas) to slowly integrate hydrogen (Zamehrian and Sedaee 2024). This can help utilize existing assets and introduce operators to hydrogen behavior while full conversion is planned. By 2030, a few storages might run on hydrogen blends if pipeline specs allow (Tarkowski and Uliasz-Misiak 2025b). With scale, the cost of salt cavern leaching per volume should come down slightly (economies in drilling, large scale leaching with multiple caverns reusing infrastructure). More importantly, the cost of hydrogen itself is expected to fall, making the opportunity cost of cushion gas lower. If green hydrogen in 2030 is say €1.5/kg (optimistic scenario in sunny/windy areas), leaving some cushion hurts less than if it's €5/kg today. Also, the more abundant hydrogen is, the more frequently storages will cycle, improving their economics (Blanchard and Megy n.d.).

On a 2050 timeline:

Europe might have a true network of hydrogen storages analogous to today's gas storage network (which is ~110 bcm methane storage across EU). This could be, for example, 50 large salt caverns and 20 repurposed gas fields operating as H_2 stores, distributed across many countries. They might collectively store hundreds of TWh of hydrogen for winter use and emergency reserves (Rolo, Costa, and Brito 2023). By then, standards and practices for UHS will be fully established. One can imagine an ISO standard for "Underground Hydrogen Storage Operations" being in place well before 2050, harmonizing how things are done. Possibly new methods like thermally insulated caverns or lined mine shafts for hydrogen might emerge if economics favor. Novel cushion strategies (some research on using liquid cushion like oil or special fluids to reduce mixing) could also technologically strengthen and make feasible UHS. Hydrogen storages might evolve into multi-product storage sites. For example, a salt cavern site could have some caverns for pure hydrogen, and adjacent caverns for CO_2 (for a carbon capture cluster), or ammonia storage tanks on surface, etc., making an integrated energy storage hub (Caglayan et al. 2020; Foh et al. 1979). Global context: By 2050, many other countries (USA, China, Middle East) will also likely have UHS if they pursue hydrogen. Europe's early work will serve as a knowledge base. Conversely, if others develop new solutions, Europe will adopt those. There will be international collaboration on safety research, materials, and maybe even shared strategic reserves (for instance, maybe North Sea offshore hubs store hydrogen for multiple nearby countries cooperatively) (Jaarsma et al. 2024). Nevertheless, south and southeastern European countries will still face a problem, since transport to the north is not cost effective, neither safe for such long distances and they should develop their own storage facilities. Examples like the Ravenna in Italy (CO2) and South Kavala (NG), Prinos in Greece (CO2) maybe a precursor to such a strategic development for the central-east Mediterranean area.

In a scenario where Europe's electricity is near 100% renewable and many sectors run on hydrogen or electricity, UHS, alongside other storage, becomes the backbone for seasonal supply. For instance, excess summer solar in Spain or Greece could be shipped as hydrogen (by pipeline or ammonia carriers) to northern Europe and stored in German salt caverns for winter – a truly integrated system. Hydrogen storage could also ensure fuel for backup power plants during multi-week dunkelflaute (dark windless periods in winter) (Hoth et al. 2023; Kukkonen 2024; Tarkowski 2019; Xie et al. 2023).

Conclusion

Underground hydrogen storage (UHS) in Europe is transitioning from a novel concept to a tangible pillar of the clean energy transition. This report has highlighted how UHS provides the means to store vast amounts of energy safely underground, ensuring that the increasing production of green hydrogen can be buffered to meet variable demand and bolster energy security. Europe's geology offers multiple avenues – salt caverns, depleted gas fields, and aquifers – each with its own advantages, and European projects are pioneering their use.

The introduction underscored UHS's role in balancing renewables and enabling a hydrogen-based energy system. We then examined the geological formations suitable for storage, finding that salt caverns shine in performance where available, while porous reservoirs offer bulk capacity using existing traps. The technical section dived into engineering considerations, concluding that no major technical barriers have been identified, though careful design around hydrogen's unique traits is essential.

We analyzed economic factors, noting that while UHS can be cost-effective at scale (particularly salt caverns for high-cycle use and depleted fields for seasonal use), supportive policies are needed to jumpstart investments. On environmental and safety aspects, we found that with proper management, UHS can operate with minimal leakage and environmental impact, leveraging decades of know-how from natural gas storage to maintain safety.

Through case studies, we saw real examples – France's HyPSTER, Austria's Underground Sun Storage, the UK's Aldbrough project, and others – which demonstrate the feasibility of UHS and provide blueprints for future expansion. The regulatory review revealed an evolving landscape: Europe is moving towards integrating hydrogen storage into its energy framework, with calls for clear targets and streamlined regulation to ensure UHS capacity is built in time to support climate goals.

Zooming into Greece, we identified that despite modest resources, Greece has promising sites (like Ionian salt formations, saline aquifers and depleted fields) that could be developed for hydrogen storage, complementing its strong renewable energy potential and improving its energy autonomy. Finally, in challenges and outlook, we discussed what lies ahead: scaling up from pilots to an EU-wide storage network, continuing to refine technologies, securing investment through policy measures, and ultimately seeing UHS become an indispensable component of a net-zero Europe by mid-century.

In essence, underground hydrogen storage is both an enabler and a beneficiary of the hydrogen economy. It enables by providing the flexibility and resilience needed for hydrogen to truly replace fossil fuels in a reliable way. It benefits because as hydrogen deployment grows, the demand for large-scale storage will grow in tandem, reinforcing its value. The synergy between renewable power, green hydrogen production, and UHS forms a sustainable energy triangle that can deliver continuous, clean energy to Europe's industries, power grids, and citizens.

Europe's commitment to research and early deployment of UHS gives it a leadership edge. The knowledge gained will not only serve Europe's needs but can guide global efforts. Countries like Japan, South Korea, and the US, which also foresee hydrogen in their energy mix, are closely watching these developments. Europe has the opportunity to standardize best practices and export its UHS expertise as other regions follow suit in decarbonizing energy systems.

In conclusion, achieving Europe's ambitious climate and energy targets will require going beyond generating renewable energy – it necessitates storing that energy in massive quantities, something underground hydrogen storage is uniquely poised to do. By harnessing the hidden expanses beneath our feet – from the salt layers under North Germany to the porous rock under the North Sea, from caverns beneath Yorkshire to aquifers under Greek soil – Europe can create an invisible energy reservoir that underpins a visible transformation to sustainability.

The road ahead will involve careful planning, continued innovation, and cross-sector cooperation, but the path is charted. Underground hydrogen storage is set to evolve from pilot projects to a widespread infrastructure backbone, securing Europe's clean energy future. As this report has detailed, the scientific, engineering, and economic foundations have been laid; the coming years will be about scaling those foundations into the full-fledged architecture of a new energy era – one where Europe's energy is not only green and abundant, but also reliably available whenever and wherever it is needed, thanks in large part to the capabilities of underground hydrogen storage.

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