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Underground Hydrogen Storage: A Strategic Evaluation of Sites and Economic Perspective

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Abstract

Drastic measures are required in the transformation of the European economy towards climate neutrality, and hydrogen is expected to play an integral part in the decarbonization process, with a political climate growing in favor towards the expansion of hydrogen-based technologies.

This master’s thesis investigates the techno-economic and strategic feasibility of Underground Hydrogen Storage (UHS) by examining the interdependencies between geological suitability, macro-environmental drivers, and economic performance. As hydrogen becomes a central pillar of the clean-energy transition, the ability to store large quantities safely, reliably, and cost-effectively is essential. The study addresses this need by evaluating three major geological formations; salt caverns, depleted gas reservoirs, and saline aquifers and identifying the factors that influence their performance as long-duration hydrogen storage systems.

A multi-layered analytical framework was applied to assess these storage types. Geological classification provided the foundation for understanding subsurface behaviour, while PESTLE analysis was used to evaluate the external political, economic, social, technological, legal, and environmental conditions that shape deployment feasibility. In parallel, a SWOT analysis examined the internal strengths and weaknesses of each formation, as well as the opportunities and threats that influence their strategic value. To quantify economic performance, a techno-economic model was developed to calculate Net Present Value (NPV) under varying market and cost assumptions. Sensitivity analysis was conducted to identify the parameters such as WACC, price spread, and capital intensity that most strongly affect financial viability.

The findings demonstrate that UHS feasibility is highly dependent on both geological characteristics and external system conditions. Salt caverns show strong technical performance but are geographically limited; depleted reservoirs offer large capacity but face geochemical and regulatory uncertainties; aquifers provide long-term potential but require further research to reduce technical risk. The integrated framework developed in this thesis provides a systematic approach for evaluating these complexities and supports informed decision-making for future hydrogen infrastructure planning.

Key words: Underground hydrogen storage, Salt cavern, Depleted reservoir, Aquifer, PESTLE, SWOT, Techno-economic analysis, Sensitivity analysis, Hydrogen economy.

Resum

Calen mesures dràstiques en la transformació de l'economia europea cap a la neutralitat climàtica, i s'espera que l'hidrogen tingui un paper integral en el procés de descarbonització, amb un clima polític creixent a favor de l'expansió de les tecnologies basades en l'hidrogen.

Aquesta tesi de màster investiga la viabilitat tecnoeconòmica i estratègica de l'emmagatzematge subterrani d'hidrogen (UHS) examinant les interdependències entre l'adequació geològica, els factors macroambientals i el rendiment econòmic. A mesura que l'hidrogen esdevé un pilar central de la transició cap a les energies netes, la capacitat d'emmagatzemar grans quantitats de manera segura, fiable i rendible és essencial. L'estudi aborda aquesta necessitat avaluant tres formacions geològiques principals: cavernes salines, reservoris de gas esgotats i aqüífers salins, i identificant els factors que influeixen en el seu rendiment com a sistemes d'emmagatzematge d'hidrogen de llarga durada.

Es va aplicar un marc analític multicapa per avaluar aquests tipus d'emmagatzematge. La classificació geològica va proporcionar la base per comprendre el comportament del subsòl, mentre que l'anàlisi PESTLE es va utilitzar per avaluar les condicions polítiques, econòmiques, socials, tecnològiques, legals i ambientals externes que configuren la viabilitat del desplegament. En paral·lel, una anàlisi DAFO va examinar els punts forts i febles interns de cada formació, així com les oportunitats i amenaces que influeixen en el seu valor estratègic. Per quantificar el rendiment econòmic, es va desenvolupar un model tecnoeconòmic per calcular el Valor Actual Net (VAN) sota diferents supòsits de mercat i costos. Es va dur a terme una anàlisi de sensibilitat per identificar els paràmetres com el WACC, la diferència de preus i la intensitat de capital que afecten més la viabilitat financera.

Les troballes demostren que la viabilitat de l'emmagatzematge subterrani d'hidrogen (UHS) depèn en gran mesura tant de les característiques geològiques com de les condicions externes del sistema. Les cavernes salines mostren un fort rendiment tècnic, però estan geogràficament limitades; els reservoris esgotats ofereixen una gran capacitat, però s'enfronten a incerteses geoquímiques i reguladores; els aqüífers proporcionen potencial a llarg termini, però requereixen més investigació per reduir el risc tècnic. El marc integrat desenvolupat en aquesta tesi proporciona un enfocament sistemàtic per avaluar aquestes complexitats i dóna suport a la presa de decisions informada per a la planificació futura d'infraestructures d'hidrogen.

Paraules clau: Emmagatzematge subterrani d'hidrogen, Caverna salina, Reservori esgotat, Aqüífer, PESTLE, DAFO, Anàlisi tecnoeconòmica, Anàlisi de sensibilitat, Economia de l'hidrogen.

Resumen

Se requieren medidas drásticas para la transformación de la economía europea hacia la neutralidad climática, y se espera que el hidrógeno desempeñe un papel fundamental en el proceso de descarbonización, dado el creciente clima político favorable a la expansión de las tecnologías basadas en hidrógeno.

Esta tesis de máster investiga la viabilidad tecnoeconómica y estratégica del Almacenamiento Subterráneo de Hidrógeno (SUH) examinando las interdependencias entre la idoneidad geológica, los factores macroambientales y el rendimiento económico. A medida que el hidrógeno se convierte en un pilar central de la transición hacia las energías limpias, la capacidad de almacenar grandes cantidades de forma segura, fiable y rentable es esencial. El estudio aborda esta necesidad evaluando tres formaciones geológicas principales: cavernas de sal, yacimientos de gas agotados y acuíferos salinos, e identificando los factores que influyen en su rendimiento como sistemas de almacenamiento de hidrógeno de larga duración.

Se aplicó un marco analítico multicapa para evaluar estos tipos de almacenamiento. La clasificación geológica sentó las bases para comprender el comportamiento del subsuelo, mientras que el análisis PESTLE se utilizó para evaluar las condiciones políticas, económicas, sociales, tecnológicas, legales y ambientales externas que determinan la viabilidad de su implementación. Paralelamente, un análisis FODA examinó las fortalezas y debilidades internas de cada formación, así como las oportunidades y amenazas que influyen en su valor estratégico. Para cuantificar el rendimiento económico, se desarrolló un modelo tecnoeconómico para calcular el Valor Actual Neto (VAN) bajo diferentes supuestos de mercado y costos. Se realizó un análisis de sensibilidad para identificar los parámetros como el WACC, el diferencial de precios y la intensidad de capital que más afectan la viabilidad financiera.

Los hallazgos demuestran que la viabilidad de los sistemas de almacenamiento subterráneo de hidrógeno (SHU) depende en gran medida tanto de las características geológicas como de las condiciones externas del sistema. Las cavernas de sal muestran un sólido rendimiento técnico, pero están limitadas geográficamente; los yacimientos agotados ofrecen gran capacidad, pero enfrentan incertidumbres geoquímicas y regulatorias; los acuíferos ofrecen potencial a largo plazo, pero requieren mayor investigación para reducir el riesgo técnico. El marco integrado desarrollado en esta tesis proporciona un enfoque sistemático para evaluar estas complejidades y respalda la toma de decisiones informada para la planificación futura de la infraestructura de hidrógeno.

Palabras clave: Almacenamiento subterráneo de hidrógeno, Caverna de sal, Yacimiento agotado, Acuífero, PESTLE, FODA, Análisis tecnoeconómico, Análisis de sensibilidad, Economía del hidrógeno.

Appreciations

This thesis work was carried out in my second-year at Universitat Politècnica de Catalunya (UPC), Spain at the department of Chemical Engineering in collaboration with Norwegian university of science and technology (NTNU) and Politecnico di Torino, Italy as part of the Erasmus Mundus Joint Master's in Hydrogen Systems and Enabling Technology (EMJM-HySET) During Autumn 2025.

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Nazmun Nahar Nelima

Glossary:

List of all abbreviations in alphabetic order:

- **CCS** Carbon Capture & Storage
- **FCF** Free Cash flow
- **IRR** Internal Rate of Return
- **LCOE** Levelized Cost of Energy
- **LCOS** Levelized Cost of Storage
- **NPV** Net Present Value
- **NWC** Net Working Capital
- **PESTLE** Political, Economic, Social, Technological, Legal and Environmental
- **SWOT** Strength, Weakness, Opportunities and Threats
- **TEA** Techno economic Analysis
- **UHS** Underground Hydrogen Storage
- **WACC** Weighted Average Cost of Capital

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1 **Introduction**

1.1 Background

The increasing global population and energy demand have led to increased usage of fossil fuels, resulting in increased greenhouse gas (GHG) emissions and intensified global warming. The International Energy Agency (IEA) reports that fossil fuels supply 80–85 % of global energy consumption, raising unprecedented concerns about the future. As fossil fuels deplete, researchers seek renewable energy sources to reduce environmental pollution caused by burning fossil fuels. Solar, wind, and geothermal are some examples of renewable energies and can play their role well as an appropriate substitute for fossil fuels and that is where Hydrogen comes in the picture [1]. By 2050, hydrogen could replace natural gas and solid fuels as an energy source. It is expected to be widely used in the chemical, metallurgical, transport industries, and in the long term also in the aviation and maritime sectors. Hydrogen is expected to play an important role in a CO_2 neutral economy, in global efforts to implement the Paris climate agreement (COP21 of 2015) and to achieve climate neutrality. This gas is considered a key element for achieving the European Green Deal and clean energy transition in the EU. Hydrogen plays a significant role in the forecasts of energy consumption until 2050[2].

In addition, the major problem with renewables is that energy generation is not correlated with energy consumption, but strongly depends on the weather, geographical localization, day time, and season. To offset the mismatch between the fluctuating energy production and demand, effective energy storage technologies for a periods of overproduction and reuse during a period of shortage is needed for which Underground Hydrogen Storage (UHS) is being considered as it has the potential for large-scale energy storage (TWh range). Underground hydrogen storage is widely regarded as the safest and most cost-effective solution in light of anticipated production capacities. Compared to aboveground gas storage, it benefits from enhanced protection against external hazards such as fires, military conflicts, and terrorist attacks due to the natural shielding provided by overlying geological formations. Additionally, it achieves higher energy density through increased storage pressure, maintains a reduced surface footprint, and incurs lower specific capital expenditure . Among the geological structures suitable for underground hydrogen storage are natural aquifers, depleted oil and gas reservoirs, abandoned mines, excavated rock caverns, and engineered salt caverns [3]

1.2 Motivation

Underground Hydrogen Storage (UHS) has emerged as a key technology to address the challenges regarding hydrogen storage, yet significant uncertainties remain regarding the optimal selection and management of storage sites. A comprehensive, multidisciplinary analysis is essential because of the complex interaction of socio-political, economic, legal, and environmental factors on different kinds of geological sites. This research is motivated by the necessity to systematically evaluate UHS options through rigorous classification, environmental scanning, and economic optimization to support the strategic and efficient integration of underground storage into hydrogen infrastructure, enabling a secure, scalable, and sustainable hydrogen economy.

1.3 Research Objectives

The goal of this thesis is to develop a comprehensive framework for the classification, evaluation, and economic optimization of Underground Hydrogen Storage (UHS) sites. Specifically, the study aims to:

1. Categorize UHS locations based on site-specific characteristics to identify their suitability and operational behaviour.
2. Conduct a detailed PESTLE analysis to examine the external macro-environmental factors affecting the feasibility and resilience of different storage types.
3. Employ a SWOT analysis to assess the intrinsic strengths, weaknesses, opportunities, and threats associated with each storage category.
4. Develop an integrated economic model to guide investment decisions by balancing cost considerations with technical performance and long-term value.
5. Provide strategic insights and recommendations to facilitate the effective deployment of UHS technology, supporting the transition towards a clean and reliable hydrogen economy.

1.4 Structure of the Thesis

The structure of the thesis is as follows:

- Chapter 2: Review of UHS storage Options: This chapter explains role of hydrogen in the field of energy and explores different storage options.

- Chapter 3: Methodology: This chapter describes the evaluation framework for UHS sites, Presents the PESTLE, SWOT and integrated economic analysis.

- Chapter 4: Results and Discussions: This chapter presents and examines the key findings from the analysis.

- Chapter 5: Conclusion and Recommendations: Chapters are concluded by summarizing the key findings and their implications and providing recommendations for both future research and practical application.

2 **Review of Underground Hydrogen Storage Options**

2.1 Hydrogen Storage Overview

2.1.1 Hydrogen as an Energy Carrier

Hydrogen is being viewed as a key energy carrier in global decarbonization efforts because it has been proven to provide low-carbon energy in different sectors. As countries opt for reduction in emissions, studies show that hydrogen-based fuels such as pure hydrogen, ammonia, and synthetic hydrocarbons play a larger role. Integrated assessment modelling indicates that hydrogen could supply around 5–15% of global final energy demand by 2050**,** with the highest shares occurring when alternatives like carbon capture and storage (CCS) or bioenergy are limited, since hydrogen can substitute for fossil fuels in carbon intensive sectors such as long-distance transport and high-temperature industrial processes [4].

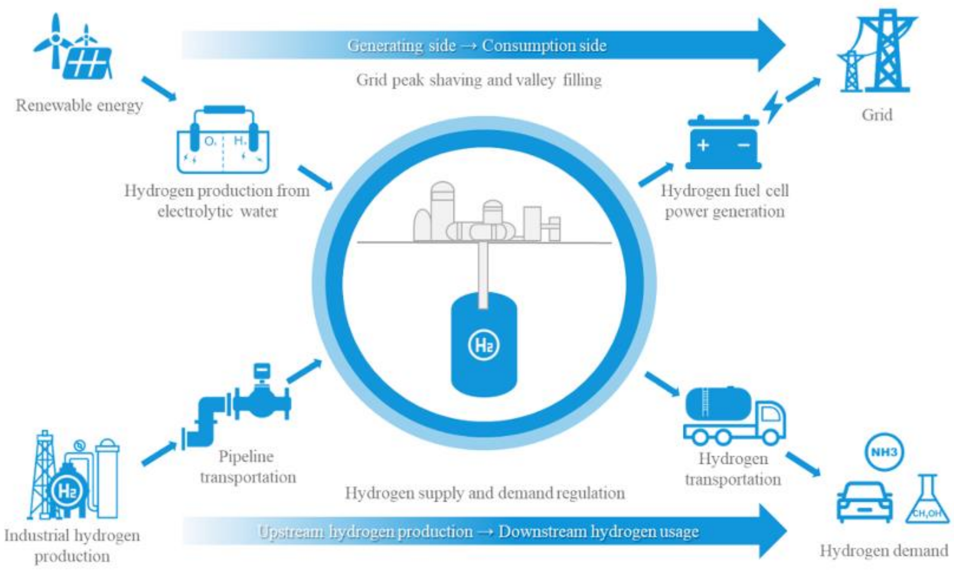

Figure 2.1: UHS to handle energy volatility and promote grid-connected renewable energy generation [5].

In transport, hydrogen becomes valuable for heavy trucks, shipping, and aviation, where batteries may not provide sufficient range or fast refuelling. Beyond these uses, hydrogen is emerging as an important tool for stabilizing electricity systems with high shares of solar and wind power. As renewable energy expands, power systems increasingly face multi-day or seasonal periods of low generation, and recent modelling shows that hydrogen can act as long-duration energy storage**,** storing surplus renewable electricity and supplying power during extended shortages; something batteries cannot economically achieve at large scale[5] [6]Because hydrogen can be produced from renewable electricity, transported, stored, and used across multiple sectors, it supports system flexibility and energy security while reducing reliance on fossil fuels. For these reasons, hydrogen is becoming a central component of many national decarbonization strategies, not as a replacement for electrification but as a complementary solution that fills critical gaps in transport, industry, and power.

2.1.2 Need for Large-Scale Storage & Storage Options overview

Hydrogen can be stored in several ways, but surface-based options such as compressed gas tanks and liquid hydrogen systems are generally suited only for small-scale or short-term applications. Compressed gas vessels are technologically mature and widely used, yet they offer limited capacity and require high pressures of 350–700 bar, while liquid hydrogen storage demands energy-intensive cooling to −253 °C and specialized cryogenic infrastructure, making both approaches costly and impractical for seasonal or grid-scale storage [1], [7], [8]. As renewable energy penetration increases, energy systems require storage solutions that can absorb large surpluses and release energy over days, weeks, or even months; durations that surface tanks cannot economically provide. Geological (underground) hydrogen storage offers a compelling alternative because formations such as salt caverns, depleted gas fields, and deep aquifers provide vast storage volumes, lower cost per unit of stored energy, and greater long-term security compared to surface systems [7], [9]. Salt caverns have already been used successfully for hydrogen storage in the UK and USA for decades, demonstrating high tightness, rapid cycling capability, and operational safety [7]

Storage Option	Features	Advantages	Disadvantages	Typical Storage Volume
Compressed Gas (Surface Tanks)	Hydrogen stored at high pressure (350–700 bar) in steel or composite vessels.	Mature technology, suitable for vehicles and refueling station.	High compression energy cost, Limited capacity.	100–1000 kg H_2 per tank (1,200–12,000 m^3 gas equivalent at STP).
Liquid Hydrogen (Cryogenic Tanks)	Hydrogen cooled to −253 °C and stored as liquid in insulated tanks.	Higher volumetric density than gas, Useful for transport and aerospace.	Very energy-intensive liquefaction, Safety concerns	1–50 tonnes H_2 per tank.
Material-Based Storage (Hydrides, Adsorbents, LOHCs)	Hydrogen stored chemically in solid compounds or liquid carriers.	High safety and energy density, Potential for compact storage.	Expensive materials, Still under development for large-scale use.	Typically 1–7 wt% H_2 (10–70 kg H_2 per tonne of storage material).
Underground Hydrogen Storage (UHS)	Hydrogen stored in geological formations such as salt caverns, depleted gas fields, or aquifers.	Cost-effective per unit of energy, Enables long-duration energy storage (LDES) for renewable grids.	Early-stage deployment in many regions, requires suitable geology, have technical challenges.	Thousands to tens of thousands of tonnes H_2 (TWh-scale potential).

Table 2.1: Comparison between Hydrogen storage options.

2.2 Classification and Technical Characteristics of UHS Sites

The most common types of UHS sites are Depleted Oil and Gas reservoirs (having the largest share of storage able sites), Salt caverns and Aquifers.

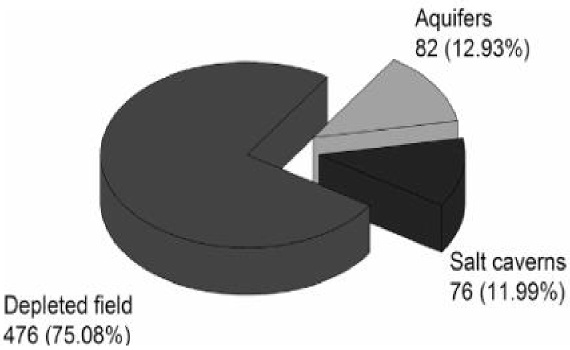

Figure 2.2: Share of worldwide UGS by storage types [7].

These sites have already proven to have stored gases underground successfully. Once H2 is injected, it is retained in the geological formation through trapping mechanisms like structural/stratigraphic, residual/capillary, solubility/dissolution, and mineral trapping[10]While research is going on the suitability of these sites to store hydrogen as well; salt caverns seem to be the most suitable option considering storage conditions.

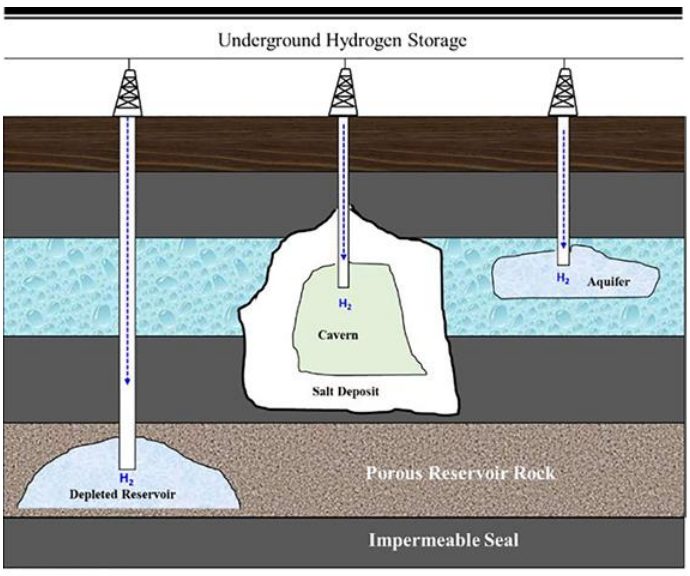

Figure 2.3: Underground hydrogen storage schematics [10].

2.2.1 Salt Caverns

Salt caverns are artificial underground cavities created within thick rock-salt formations. They are typically formed through solution mining, a process in which fresh water is injected into the salt layer to dissolve the salt and pump out the resulting brine. Over time, this creates a large, smooth-walled cavern suitable for storing gases. Two main geological settings host these caverns: salt domes, which are thick, vertically uplifted salt bodies with excellent purity and mechanical stability, and bedded salt formations, which consist of layered salt interbedded with other rocks. Salt domes generally allow for larger and more stable caverns, while bedded salts require more careful design due to their heterogeneity [7], [11].

Salt caverns are currently the most mature and proven option for underground hydrogen storage. They have already been used successfully for decades in the UK and the United States, demonstrating that hydrogen can be stored safely with minimal losses and without significant chemical reactions with the surrounding rock [3]. Their key advantage is high deliverability: hydrogen can be injected and withdrawn rapidly, making salt caverns ideal for balancing short-term fluctuations in renewable energy supply. Their extremely low permeability, combined with the self-healing nature of salt, ensures excellent containment and very low leakage risk [7], [11]

Despite these advantages, several challenges remain. The initial capital cost of developing a salt cavern is high because it requires deep drilling, well construction, and extensive solution-mining operations [11]. Solution mining also demands a large and continuous supply of fresh water, and the extracted brine must be disposed of safely; either through industrial use, reinjection, or discharge where permitted which can be environmentally and logistically complex [3]. As hydrogen storage shifts toward supporting renewable-energy systems, caverns will need to operate with more frequent cycling. This increases mechanical stress on the cavern walls and surrounding rock, requiring improved geo-mechanical characterization, monitoring, and modelling to ensure long-term stability and prevent issues such as excessive creep, roof deformation, or wellbore integrity problems [12]

2.2.2 Depleted Gas Reservoirs

Depleted gas reservoirs are porous and permeable sedimentary formations; typically, sandstones or carbonates that previously held natural gas under geological trapping conditions. Their structure includes a reservoir rock overlain by a low-permeability caprock, which historically ensured long-term containment. Because these reservoirs have been extensively studied during their production life, their geometry, pressure history, and sealing capacity are generally well understood [7], [12].

These reservoirs offer significant potential for hydrogen storage due to their very large pore volumes, making them suitable for seasonal-scale storage. Existing infrastructure such as wells and pipelines can often be repurposed, reducing development time and cost. Numerical studies show that depleted reservoirs can store hydrogen effectively, with withdrawal performance strongly influenced by reservoir depth, permeability, dip angle, and well placement [13]. Steeply dipping structures, for example, help hydrogen accumulate near the crest, improving recovery during withdrawal. Their large size also makes them attractive for long-duration energy storage needed to balance seasonal variations in renewable energy supply [14].

However, depleted reservoirs also present several challenges. Residual methane and other hydrocarbons can mix with injected hydrogen, reducing purity and requiring gas-processing steps during withdrawal [7]. Microbial activity is a major concern: hydrogen-consuming microorganisms such as sulfate-reducing bacteria and methanogens can convert hydrogen into methane, hydrogen sulfide, or acetate, leading to storage losses and potential souring of the reservoir [15]. Geomechanical risks also arise because cyclic injection and withdrawal can alter pore pressure, potentially reactivating faults or compromising caprock integrity [12].

2.2.3 Deep Saline Aquifers

Deep saline aquifers are porous rock formations saturated with brine and sealed by an overlying caprock. They are widespread across sedimentary basins and often have very large storage capacities, making them a promising long-term option for large-scale hydrogen storage. Their geological properties such as porosity, permeability, and caprock integrity vary widely and are generally less well characterized than depleted reservoirs, requiring new exploration and modelling [7], [12].

Aquifers offer the advantage of enormous potential storage volumes and broad geographic availability. Their pore systems can theoretically accommodate large quantities of hydrogen, and their natural water saturation can help limit hydrogen diffusion due to low solubility in brine. In some cases, aquifers have been used historically for town-gas storage, providing partial analogues for hydrogen storage [3]. Modelling studies show that aquifers can support seasonal hydrogen storage, with recovery efficiency depending on reservoir structure, injection strategy etc [13].

Nevertheless, aquifers face the greatest technical uncertainty among the three storage types. Because they have not been previously developed, extensive site characterization is required to confirm caprock integrity, reservoir continuity, and pressure-management capacity. Microbial activity poses a significant risk: brine-filled environments can host hydrogenotrophic microbes that rapidly consume hydrogen, as demonstrated in pore-scale experiments showing substantial hydrogen loss within days [15]. Geochemical reactions between hydrogen, brine, and minerals may also alter reservoir properties or generate unwanted by-products [12]. Additionally, aquifers typically allow only one or two injection-withdrawal cycles per year, limiting their suitability for high-frequency energy-storage applications [7].

Criteria	**Salt Caverns**	**Depleted Gas Reservoirs**	**Deep Saline Aquifers**
Geographical availability	Low	Medium	High
Storage capacity potential	Medium	High	Very High
Deliverability (injection/withdrawal rates)	Very High	Medium	Low
Suitability for pure H_2 storage	Excellent	Medium	Low
Repurposing potential	Low	Very High	Medium
Maturity level	High	Medium	Low
Cushion gas requirement	Low	High	High
Hydrogen loss risk (microbial, dissolution)	Very Low	Medium–High	High
Monitoring & modelling complexity	Medium	High	Very High

Cycling frequency suitability	Excellent	Low–Medium	Low
Capex	High	Medium	Medium–High
TRL	8 (Commercial)	6-7	3-5

Table 2.2: Comparison of key features of different types of UHS sites**.**

2.3 Overview of Literature

The literature review conducted as part of this thesis reveals a significant research gap. The new technology of Underground hydrogen storage lacks specific academic literature that examines the External, Internal and Economic aspects of UHS which affects investment decisions.

The literature review includes two different types of studies which are the external or internal factors analysis and techno-economic analysis of potential storage sites which gives ideas on how the outlook is on UHS and what the market situation is.

The lack of particular literature concerning an integrated study led to the expansion of the review into more general assessment research. This broadened scope allowed for doing an elaborate study on the macro and micro factors regarding UHS and analyzing the UHS in an NPV framework where most of the study focuses on LCOS which seems to be insufficient as proper economic model for UHS. Through its critical analysis of PESTLE, SWOT and integrating them into the economic model for decision making, this thesis aims to bridge the identified research gap.

Authors	**Methods**	**Highlights**
[2]	Factors analysis	Discusses about the External Factors of UHS that could be viewed as barriers.
[16]	Factors analysis	Demonstrates Social and environmental aspects of UHS; insights from storage of CO2
[17]	Factors analysis	Provides Insight into geological sites mechanisms, economic and barriers.

[18]	Factors+Economic	Review and prospects of the role of underground salt caverns for large-scale energy storage.
[19]	Techno economic	Insight into Underground Hydrogen Storage in Aquifers: Current Status, Modeling, Economic Approaches.
[20]	Techno economic	Techno economic Analysis of different types of storage sites.
[21]	Techno economic	Analyzing The viability of UHS as an energy option to meet city demand.
[22]	Techno economic	Demonstrates a Market-based asset valuation of hydrogen geological storage.

Table 2.3: Literature Overview.

3 Methodology

3.1 Research Design and Analytical Flow

The Research method is a sequential analysis of the qualitative examination of Extrinsic and intrinsic Factors concerning UHS and then a quantitative NPV framework to determine financial viability and the integration of the PESTLE and SWOT insights to inform the assumptions and risk factors incorporated into the NPV model.

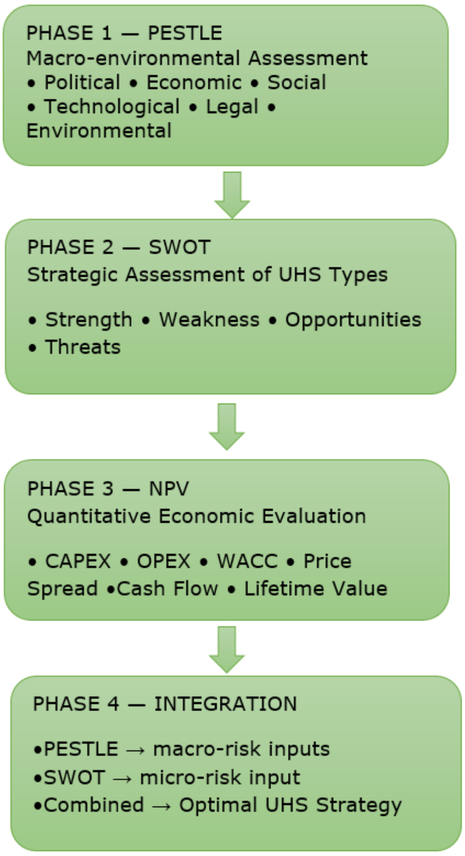

Figure 3.1: Analytical Workflow.

PESTLE

3.1.1 Policy/Political factors regarding UHS

Underground hydrogen storage (UHS) has emerged as a strategic component of Europe's long-term decarbonization agenda, particularly as the EU accelerates its transition toward a climate-neutral energy system by 2050. Although hydrogen policy has advanced rapidly in recent years, the regulatory landscape for UHS remains fragmented and underdeveloped. Instead of a dedicated legislative framework, UHS is currently shaped by a combination of broader hydrogen, gas market, infrastructure, and energy system integration policies. Understanding how these policies interact and where gaps persist is essential for assessing the political conditions that will influence the deployment of UHS across Europe.

Existing EU Policies Relevant to UHS

At present, the EU does not have a single, dedicated legislative instrument governing underground hydrogen storage. This absence is widely acknowledged in policy analyses, which note that UHS continues to fall under a patchwork of national mining laws, geological storage regulations, and gas infrastructure rules rather than a harmonized EU-level framework [23], [24]. The Hydrogen Europe Infrastructure Report explicitly highlights this regulatory vacuum, emphasizing that the lack of a clear framework for hydrogen storage is one of the most significant barriers to investment and long-term planning [24].

Despite the absence of UHS-specific legislation, several EU policies indirectly shape the development of underground storage. The EU Hydrogen Strategy (2020) recognizes hydrogen storage as a critical enabler of sector integration, seasonal balancing, and energy security, although it does not define specific rules for geological storage. Instead, it calls for large-scale hydrogen infrastructure planning, the repurposing of natural gas assets, and the integration of hydrogen into the broader energy system [25]. The Hydrogen and Decarbonized Gas Market Package (2023–2024) introduces rules for hydrogen network operators, third-party access to hydrogen infrastructure by 2033, and provisions for hydrogen quality and interoperability. However, these measures primarily address pipelines and market organization, leaving geological storage largely unregulated.

Nevertheless, because UHS is not yet harmonized at EU level, permitting and geological regulation remain the responsibility of Member States, which apply their own mining, environmental, and subsurface laws; often adapted from natural gas storage frameworks [23], [26].

Advocacy for Dedicated UHS Policy

The absence of a dedicated UHS regulatory framework has prompted strong advocacy from industry associations, research consortia, and system operators. Hydrogen Europe has repeatedly urged the European Commission to develop an EU-wide storage strategy that translates into concrete legislative measures [24]. Similarly, the Frontier Economics and Artelys study commissioned by GIE stresses that policy intervention is essential, as the market alone cannot deliver the storage capacity required to support Europe's decarbonization pathway [26]. The HyUSPRe consortium also highlights the need for harmonized technical standards, clear permitting rules, and a coherent regulatory framework to support the commercial deployment of UHS in porous reservoirs [27]. Together, these voices reflect a growing consensus that UHS requires dedicated policy attention if it is to fulfil its strategic role in the European energy system.

Permitting and Planning Policies for UHS

Permitting for UHS currently relies on a combination of national mining legislation, environmental impact assessment requirements, and gas storage regulations. Because these frameworks were not designed with hydrogen in mind, developers face significant uncertainty when navigating approval processes. Permitting porous reservoir storage is particularly complex, often involving lengthy procedures, unclear responsibilities, and inconsistent interpretations of geological risk and liability across Member States [27]. This lack of standardization slows project development and increases investment risk. The lead times of UHS asset development are currently up to 10 years; As permitting procedures take up a significant part of the development timeline, it needs to be ensured that national administrative barriers to projects are as low as possible [28]

The policy gaps in permitting are substantial. There is no EU-wide permitting framework for hydrogen caverns or porous reservoirs, no harmonized rules for repurposing natural gas storage sites, and no hydrogen-specific safety or monitoring standards. National authorities often lack experience with hydrogen storage, leading to cautious and sometimes overly restrictive interpretations of existing laws [24].

Tax rate and WACC for UHS projects

Since no dedicated policies exist for Underground Hydrogen economy, the instability in policies may affect investment decisions and hence business prospects. For example, In the EU, the corporate tax rate varies widely in members states ranging from 20-30% [29] In the same fashion, the WACC for a project could range from 6-10% which is a wide range. And since the hydrogen market currently follows country specific regulations, the cost of a project could widely vary depending on location.

Storage Targets and Policy Mechanisms

The EU Hydrogen Strategy does not set explicit storage targets, but recent modelling studies provide quantitative benchmarks for what the system will require. According to the Frontier Economics and Artelys analysis, an optimized European energy system would need approximately 45 TWh of underground hydrogen storage capacity by 2030 and around 270 TWh by 2050 [26]. These figures reflect the role of UHS in providing seasonal flexibility, supporting electrolyser operation, and ensuring security of supply.

However, the gap between these targets and current project pipelines is substantial. Announced projects amount to only 9 TWh of capacity by 2030 and 21.5 TWh by 2050, leaving a shortfall of 36 TWh in 2030 and 248.5 TWh in 2050 [26]. This discrepancy underscores the need for stronger policy intervention. At present, there are no binding EU storage targets, no mandatory national contributions, and no dedicated funding mechanisms for UHS. System operators are not required to include UHS in network development plans, and Member States lack coordinated strategies for scaling storage capacity. Hydrogen Europe has therefore called for a “2030 EU Underground Hydrogen Storage Plan” that would establish binding targets and integrate UHS into broader hydrogen infrastructure planning [24].

Hydrogen Purity Regulations

Hydrogen purity is regulated through a combination of European standards and industry guidelines. National gas quality standards also influence purity requirements, particularly where hydrogen is blended with natural gas.

Purity is a critical issue for UHS because impurities can affect both storage integrity and end-use applications. HyUSPRe notes that contaminants such as oxygen, carbon dioxide, or moisture can trigger geochemical or microbiological reactions in porous reservoirs, potentially affecting storage performance and safety [24]. Industrial users, such as ammonia producers or steel manufacturers, also require hydrogen of consistent and high purity. Despite these considerations, there is currently no EU-wide purity standard for hydrogen withdrawn from geological storage, creating uncertainty for operators and end-users.

Government Support and Funding Mechanisms

Government support for UHS is primarily channeled through broader hydrogen and energy infrastructure funding programs. At the EU level, funding programs such as the Innovation Fund, the Connecting Europe Facility (CEF), InvestEU, and Horizon Europe provide financial support for hydrogen production, transport, and storage projects[24].

National governments also play an important role by funding pilot projects, supporting hydrogen valleys, and enabling the repurposing of natural gas infrastructure. Examples include the HyStorage project in Germany and the Underground Sun Storage initiative in Austria, both of which receive national and EU support.

Research, Innovation, and Demonstration Policies

Research and innovation are central to advancing UHS technologies, particularly for porous reservoirs, where technical uncertainties remain. The EU invests heavily in hydrogen R&I through Horizon 2020, Horizon Europe, the Clean Hydrogen Partnership, and collaborations under the IEA Hydrogen TCP. The HyUSPRe project, funded under the Fuel Cells and Hydrogen Joint Undertaking, exemplifies the EU's commitment to developing the scientific and technical foundations for UHS deployment [27]. Its roadmap emphasizes the need for improved reservoir modelling, materials research, monitoring technologies, and environmental impact assessment tools.

Budget allocations for hydrogen research are substantial. The EU Hydrogen Strategy estimates that €180–470 billion will be invested in renewable hydrogen production by 2050, with an additional €65 billion required for hydrogen transport, distribution, and storage by 2030 [25]. However, no specific budget is earmarked exclusively for UHS, highlighting another policy gap that may hinder the scaling of storage capacity.

Policy Aspect	Summary
Dedicated UHS Strategy	No standalone EU strategy; addressed within broader hydrogen policies.
Inclusion in Legislation	Mentioned in Gas Market Package and TEN-E; no binding UHS regime.
Industry Advocacy	Calls for dedicated policy, clear targets, and streamlined permitting.
Permitting & Planning	Slow, complex processes; need for harmonization and acceleration.
Tax rate, WACC	No dedicated value for UHS, wide range exists
Financial Support	EU funds available (CEF, Horizon Europe); no UHS-specific incentives.

Storage Targets	Modelled need: 45 TWh by 2030, 270 TWh by 2050; no binding targets.
Integration with Infrastructure	Mix of repurposed gas sites and new storage recommended.
Research & Innovation	Supported via Horizon Europe, Clean Hydrogen Partnership, HyUSPRe.
Hydrogen Purity Standards	No EU-wide rules; industry calls for harmonized standards.

Table 3.1: Highlights of EU UHS Policies.

3.1.2 Economic Aspects

Investment Dynamics and Funding Availability

The economic feasibility of underground hydrogen storage in Europe is strongly shaped by the availability of investment and the scale of public financial support. Although Europe hosts a large pipeline of hydrogen projects, most remain at the planning stage because developers lack the long-term revenue certainty required to reach final investment decisions. EU's hydrogen ambitions demands producing, transporting, and consuming 10 million tonnes of renewable hydrogen by 2030 will require EUR 335-471 billion in total investment, including EUR 50-75 billion for electrolysers, EUR 28-38 billion for pipelines, and EUR 6-11 billion for storage infrastructure [30]. Despite this, early renewable hydrogen projects still require substantial financial support to overcome the "green premium," and a budget of EUR 1 billion enables only 0.04-0.06 million tonnes of renewable hydrogen production capacity per year [30]. This mismatch between investment needs and available funding slows the development of UHS, as storage operators cannot justify capital expenditure without predictable demand and stable revenue streams. Only a small fraction of announced hydrogen projects in Europe have reached final investment decision due to insufficient policy implementation and limited offtake certainty [31].

Infrastructure Costs, Hydrogen Price spread and Cost Structure

Infrastructure costs are a central determinant of UHS economics. Capital expenditure of a project varies widely depending on geology, depth, and required upgrades. Across Europe, capital costs range from USD 10 million to USD 1 billion [32]. Salt caverns typically incur higher capital costs because they require more compressors and support higher cycling rates, but they benefit from lower levelized costs of storage (LCOS) due to their ability to cycle hydrogen multiple times per year. Porous reservoirs, by contrast, have lower upfront costs but higher LCOS because they cycle more slowly and require larger volumes of cushion gas. The LCOS for salt caverns averages EUR 0.68/kg, while porous reservoirs average EUR 1.28/kg.

Hydrogen price spread also plays a significant role in storage economics. Current renewable hydrogen cost ranges between 4-7 EUR/kg. Because hydrogen itself represents a substantial share of total capital costs, high hydrogen prices directly increase the cost of establishing storage. As renewable hydrogen production scales and learning effects reduce costs, storage economics are expected to improve. The study projects that LCOS could fall to EUR 0.34/kg after three learning cycles, demonstrating the potential for significant cost reductions as the hydrogen economy matures [32].

Financing Conditions, Discount Rates, and the Role of Capital Costs

Financing conditions exert a powerful influence on UHS project viability, particularly because hydrogen infrastructure is capital-intensive and characterized by long payback periods [32]. A higher discount rate increases the levelized total capital cost (LTCC), making UHS less competitive compared to other flexibility options. Salt caverns have a much higher capital costs, but they are mature and proven technology to store hydrogen hence financing conditions can affect storage project deployment greatly [20] Since financing conditions are not merely a background factor but a central determinant of whether UHS projects proceed to construction, the European Hydrogen Bank is working on to reduce financing barriers by providing predictable revenue streams and improving investor confidence, thereby lowering the effective cost of capital for early hydrogen projects[30].

Economic Barriers, Market Gaps, and Maturity of the Hydrogen Economy

Despite growing policy support, significant economic barriers continue to hinder the development of UHS in Europe. One of the most persistent challenges is the lack of mature hydrogen demand. Only 3.6% of the supply planned for commissioning by 2030 has reached final investment decision, and only 4.5% of the supply needed to meet REPowerEU's 2030 demand target has secured binding offtake agreements [31]. This demand uncertainty creates a structural problem: storage operators cannot justify investment without clear offtake, while hydrogen producers and consumers hesitate to commit without available storage.

Market fragmentation across Member States causes further economic risk. National support schemes differ widely in design, scale, and eligibility, creating inconsistent investment situation and slowing cross-border infrastructure development. The absence of binding EU-wide storage targets also contributes to under investment. While studies indicate a need for 45 TWh of UHS capacity by 2030 and 270 TWh by 2050, current project pipelines fall far short of these values [32]. Without coordinated target-setting, developers face uncertainty about future market size and revenue potential.

Another barrier is the risk of stranded assets. Repurposed natural gas infrastructure may not recover its capital costs if hydrogen demand fails to materialize at scale. This risk is heightened by the slow pace of electrolyser deployment, the high cost of renewable hydrogen, and the limited progress on hydrogen infrastructure. Although USD 320 billion in hydrogen investments have been announced globally, only USD 29 billion has reached final investment decision, reflecting the early-stage nature of the sector and the need for stronger economic incentives [33].

Economic Aspect	**Summary**
Funding Availability	EU funding programs support early projects, but funding remains insufficient to close the green premium.
Project Maturity	Only 3.6% of planned 2030 hydrogen supply has reached FID, and only 4.5% has secured binding offtake agreements.
Infrastructure Costs	UHS capital costs range from EUR 10 million to EUR 1 billion.
Storage Cost Levels	Levelized costs average 0.68/kg for salt caverns and USD 1.3/kg for porous reservoirs.
Market Gaps	Lack of binding storage targets and fragmented national support schemes create uncertainty for investors.
Risk of Stranded Assets	Repurposed gas infrastructure faces economic risk if hydrogen demand does not scale as expected.
Future Cost Reductions	Learning effects could reduce LCOS to EUR 0.34/kg after several experience cycles.

Table 3.2: Highlights of Economic aspects of UHS in the EU.

3.1.3 Social Aspect

Public Acceptance and Risk Perception

Public acceptance plays a decisive role in determining whether underground hydrogen storage projects can move from planning to implementation. Even though hydrogen is widely associated with clean energy and innovation, communities often react cautiously when a storage site is proposed nearby. Concerns typically revolve around safety, unfamiliar subsurface activities, and potential environmental risks; especially in regions with little experience hosting geological storage infrastructure. Research on hydrogen technologies shows a consistent general-local acceptance gap, where people support hydrogen in principle but become more hesitant when a facility is planned close to their homes [34]. This pattern mirrors earlier findings in renewable energy and CCS, where local acceptance depends heavily on trust, perceived fairness, and the quality of engagement rather than on technical risk alone [16], [35].

Risk perception is shaped less by engineering facts and more by trust, familiarity, and the perceived credibility of project developers. Studies on CCS show that when developers openly share safety data, involve local stakeholders early in the planning process, and demonstrate that communities will benefit directly, acceptance increases significantly. The HyPSTER project in France; one of Europe's first green hydrogen storage demonstrations explicitly integrated community engagement and transparency into its design, recognizing that social acceptance was as important as technical feasibility [16]. Conversely, projects that rely solely on meeting legal permitting requirements, without meaningful engagement, often encounter delays or opposition. In some CCS cases, providing risk information without context even reduced acceptance, as people interpreted the information as evidence of danger rather than transparency [16].

Job Creation and Regional Economic Development

Communities often evaluate UHS projects through the lens of local economic opportunity. People are more supportive of new energy infrastructure when they see clear benefits for their region, such as job creation, training opportunities, and long-term industrial activity [36]. This dynamic is already visible in Europe's emerging hydrogen economy. For example, the H2eart for Europe report highlights that UHS development is concentrated in regions with existing gas storage expertise such as Germany, the Netherlands, and France where operators like Uniper, Storengy, and VNG Gasspeicher are positioning UHS as a way to preserve industrial jobs and repurpose existing skills [37]. These regions view UHS not only as an energy asset but also as a tool for economic resilience during the transition away from fossil fuels.

Experience from CCS and natural gas storage also shows that local economic benefits can significantly increase acceptance. In Poland, for instance, communities living near combined CO_2 and natural gas storage sites expressed more positive attitudes when they understood that the project could bring employment and local investment [16]. UHS can play a similar role by anchoring new hydrogen value-chain activities such as electrolysis, transport, and industrial use in regions that host storage facilities.

Social Decarbonization Benefits

UHS also carries broader social benefits linked to Europe's decarbonization goals. Hydrogen is increasingly recognized as a key enabler of deep emissions reductions in hard-to-abate sectors such as steelmaking, chemicals, and heavy transport, and its role in stabilizing renewable-based energy systems is widely acknowledged [16]. Public support for hydrogen tends to increase when people understand its contribution to climate mitigation, energy security, and reduced dependence on fossil-fuel imports [36].

The benefits resonate strongly with European citizens, who generally support climate action but expect solutions that are reliable, affordable, and fair. By enabling long-duration storage of renewable hydrogen, UHS strengthens the reliability of clean energy systems and helps align local communities with national and European climate ambitions.

Local Investments and Community Benefits

Local investment is another important factor shaping social acceptance. Communities are more likely to support UHS when they perceive direct, place-based advantages such as infrastructure upgrades, local procurement, or community development initiatives. Trust in local authorities and operators strongly influences acceptance, especially when people believe their concerns will be taken seriously [34]. This aligns with broader findings in renewable energy research, where place attachment and the perceived fairness of decision-making processes play a major role in shaping local responses [35]. Even though UHS infrastructure is largely underground and visually out of sight, communities still expect transparency about land use, safety protocols, and long-term monitoring responsibilities.

Several European hydrogen storage pilots already recognize this. The HyStock project in the Netherlands incorporated public consultation and transparency into its planning process, acknowledging that community trust was essential for long-term success [16]. Similarly, the H2CAST Etzel project in Germany emphasizes local engagement and communication as part of its development strategy, reflecting lessons learned from earlier CCS controversies. Projects that actively involve municipalities, offer local economic participation, or integrate community benefit schemes tend to face fewer barriers and enjoy stronger long-term support.

Knowledge Gaps, Social Barriers, and Market Maturity

Across all studies, a recurring theme is the presence of significant knowledge gaps surrounding hydrogen technologies. Public understanding of hydrogen production, storage, and safety remains limited, and this lack of familiarity is a major barrier to acceptance [36]. Research shows that people often rely on trust in institutions when forming opinions about unfamiliar technologies, making education and communication essential. It seems that people express more concerns about technologies they do not fully understand, and local acceptance improves when information is clear, accessible, and tailored to community needs [34].

Also, despite growing interest, UHS remains at an early stage of social maturity, and several other barriers persist. These include low public awareness, limited research on social impacts particularly in rural or marginalized communities, unclear regulatory frameworks, and concerns about long-term safety and monitoring inherited from CCS debates [16], [36]. Acceptance is often lower when people feel excluded from decision-making or when they perceive that risks and benefits are unevenly distributed [34].

UHS deployment is currently far behind what is needed for 2030, and that delays in permitting and public acceptance could widen this gap further [37]. Addressing these barriers will require interdisciplinary research, targeted public engagement strategies, and policy frameworks that explicitly incorporate social acceptance alongside technical and economic considerations. As seen in CCS, failing to address social readiness can delay or derail projects even when technological readiness is high.

Social Aspect	Summary
Public acceptance	Community attitudes depend on trust, perceived safety, and familiarity with subsurface technologies.
Risk perception	Safety concerns and uncertainty influence acceptance more than technical risk assessments.
General–local gap	Support for hydrogen is higher in general than for projects located near communities.
Stakeholder engagement	Early involvement and transparent communication improve acceptance and reduce opposition.
Job creation	UHS can support regional employment and preserve existing gas-sector expertise.
Regional development	Storage projects can stimulate local economies and attract hydrogen-related industries.
Decarbonisation benefits	UHS supports renewable integration and strengthens public support for climate goals.
Local benefits	Acceptance increases when communities see tangible advantages such as investment or infrastructure improvements.
Knowledge gaps	Limited public understanding of hydrogen storage highlights the need for education and demonstration projects.
Social readiness challenges	Low awareness, uneven benefit distribution, and legacy concerns from CCS shape social barriers.

Table 3.3: Social Aspect of UHS.

3.1.4 Technological Aspect

Technological Maturity of Salt Caverns, Depleted Reservoirs, and Aquifers

The technological maturity of underground hydrogen storage (UHS) varies significantly across geological settings and storage types, and this maturity directly shapes both technical performance and economic feasibility. Salt caverns are the most technologically advanced option, with decades of operational experience in natural gas storage and several long-running hydrogen caverns in the UK and USA. The properties of the surrounding salt include low permeability and such high sealing capability, inert chemical behavior with respect to hydrogen and favorable mechanical properties that provide the ability to accommodate repeated withdrawal and extraction make them the most reliable and lowest-risk UHS technology, enabling high deliverability and frequent cycling with minimal losses [38]. This high maturity reduces uncertainty and lowers financing costs, improving economic viability.

Depleted gas reservoirs have a moderate maturity level. Although widely used for natural gas storage, hydrogen introduces new uncertainties related to geochemical reactions, microbial activity, where additional characterization might be needed and that increases operational risk [13], [17]Numerical simulations show that reservoir structure, permeability and pressure strongly influence hydrogen recovery and withdrawal performance [13]These uncertainties increase the cost of storage, but depleted reservoirs is still attractive for large-scale seasonal storage due to their capacity of storing in large quantity, which is essential for stabilizing hydrogen markets with high renewable penetration.

Aquifers are the least mature option concerning UHS. Their geological heterogeneity, limited historical data, and uncertain caprock integrity introduce significant technical and economic risks. Past town-gas storage projects demonstrate feasibility, but there is not enough recent data or evidence to support their use as potential storage options[17], [38].

Cushion Gas Requirements

For maintaining reservoir pressure, ensuring stable injection and withdrawal performance of UHS sites, Cushion gas is essential. The required volume varies widely across storage types and has major economic implications. Salt caverns require the smallest cushion gas fraction (typically 20–30%) because salt is impermeable and hydrogen absorption does not occur. This results in a high working-to-cushion gas ratio and lower upfront capital requirements [39]

In depleted reservoirs, cushion gas requirements are significantly higher (around 50%) because the formation must be re-pressurized after hydrocarbon production. Hydrogen mixing with residual methane or injected nitrogen reduces withdrawal purity and increases purification costs [13], [40]Methane often provides the highest recovery but also has higher chances of getting mixed with hydrogen, while nitrogen offers better purity but lower recovery [40]. These trade-offs directly affect the levelized cost of storage.

Aquifers require the largest cushion gas volumes; often exceeding 50-80% because the formation must be pressurized from hydrostatic conditions to operational storage pressure [17], [39]This dramatically increases capital intensity and reduces the economically recoverable hydrogen fraction.

Injection and Withdrawal Rates

The deliverability of UHS system is determined by Injection and withdrawal rates and it strongly influence the economic role of UHS in the hydrogen market. Salt caverns offer the highest deliverability due to their engineered geometry and negligible flow resistance, enabling rapid cycling [38]Depleted reservoirs exhibit moderate deliverability constrained by permeability, reservoir dip, and pressure gradients which means lower injection and withdrawal rates and that can add up to more OPEX (lower rate means adding more wells to the structure) resulting economic constrains[13]. However, deliverability remains lower than in salt caverns, limiting their suitability for high-frequency cycling. Aquifers typically have the lowest and most uncertain deliverability due to heterogeneity and pressure limitations [17]Slow withdrawal rates reduce the ability to respond to market price spikes, limiting economic value to seasonal storage.

Deliverability directly affects revenue potential since higher rates enable more cycles and greater exploitation of hydrogen price spreads.

Cycling Frequency

Cycling frequency is the number of injection-withdrawal cycles per year. It has a major impact on revenue generation and cost recovery. Salt caverns can support multiple cycles per year (up to 10–12), enabling operators to exploit frequent price spreads and maximize revenue [2], [38]Depleted reservoirs typically support one to two cycles per year due to geomechanical and pressure constraints. This aligns them with seasonal storage applications but limits short-term market participation. Aquifers generally support only one cycle per year, making them suitable exclusively for long-duration seasonal balancing [17]

Efficiency, Purity, and Loss Mechanisms

Technological efficiency is defined by working gas fraction, withdrawal purity, and losses. Salt caverns exhibit the highest efficiency because hydrogen does not react with salt, microbial activity is negligible, and mixing losses are minimal [38]Depleted reservoirs experience moderate efficiency losses due to hydrogen mixing with cushion gas, dissolution in formation water, and microbial consumption which could affect in significant amount [17]Numerical studies show purity declines over time, especially when methane is used as cushion gas [40]Aquifers face the greatest efficiency challenges due to heterogeneity, dissolution, and microbial activity, which can significantly reduce the recoverable hydrogen fraction and degrade purity [39]

Hydrogen Embrittlement, Leakage, and Material Integrity

There are several technological challenges associated with UHS; hydrogen embrittlement and leakage risks are among them. These directly affect cost, safety, and long-term viability. Hydrogen can cause embrittlement of steel casings, tubing, and wellhead components, especially under high pressure and cyclic[17], [38]. This increases maintenance costs and requires specialized materials.

Leakage risks are lowest in salt caverns due to the extremely low permeability of salt, but wellbore integrity should be maintained to ensure the protection of the equipment [38]In depleted reservoirs and aquifers, leakage can occur through wells, faults, or caprock diffusion, increasing monitoring costs and regulatory burdens [2]

Hydrogen losses reduce the effective working gas fraction and increase the cost per kilogram delivered. These challenges also affect market confidence; higher perceived risk increases financing costs, raises WACC, and slows investment, delaying the development of a robust hydrogen economy.

Technological Factor	Salt cavern	Depleted reservoir	Aquifer
Cushion gas needs	Low (20–30%); minimal mixing and losses.	Medium-high; mixing with methane/N_2 affects purity and recovery.	Very high (50–80%); major cost driver due to pressurization needs.
Injection & withdrawal rates	Very high; ideal for fast cycling and high deliverability.	Moderate; controlled by permeability, dip, and reservoir pressure.	Low; limited by heterogeneity and pressure buildup.
Cycling frequency	High (up to 10–12 cycles/year).	Medium (1–2 cycles/year).	Low (1 cycle/year).
Efficiency & purity	Highest; minimal reactions or mixing.	Moderate; mixing, dissolution, and microbial effects reduce purity.	Lowest; dissolution and microbial activity cause major losses.
Hydrogen losses	Very low; salt is impermeable.	Moderate; mixing and microbial conversion to methane.	High; dissolution, biological losses, and lateral spreading.
Embrittlement & integrity	Low geological risk but still some wellbore risk.	Higher risk due to wells leakage and cyclic loading.	Highest risk; uncertain well and caprock conditions.

Table 3.4: Technological aspects of UHS.

3.1.5 Legal aspects

Underground hydrogen storage faces drawbacks and legal challenges because no country including EU Member States has a complete, dedicated legal framework for UHS yet. Most governments still rely on rules originally written for natural gas storage or CO_2 storage, even though underground hydrogen storage regulations should be unique as its nature is different than natural gases. The lack of concise legal framework creates uncertainty for investors, regulators, and operators, because it is unclear which rules apply at each stage of a UHS project[41].

land-use rights and subsurface ownership

A major legal issue is land-use rights and subsurface ownership. In many jurisdictions, the ownership of land does not automatically include ownership of the deep underground layers where hydrogen would be stored. Some countries treat the subsurface as state property, while others allow private mineral rights. This means developers must secure permits, concessions, or leases before they can inject hydrogen underground. EU Member States differ widely in how they define these rights, which complicates cross-border hydrogen infrastructure planning. There are no current law clearly stating whether hydrogen stored underground remains the property of the operator, the state, or the storage customer during its time underground. This uncertainty affects insurance, taxation, and commercial contracts[42].

Permitting process

Long, unclear, and inconsistent permitting process is another key challenge. Hydrogen projects frequently face delays because authorities are unsure which laws apply [43] where there is environmental law, mining law, industrial emissions law and gas-market law which were primarily designed for other purposes might not be consistent with UHS and that can create confusion. Many local authorities also lack experience with hydrogen, leading to cautious decision-making and repeated requests for additional studies. This creates investment uncertainty and slows down deployment.

Liability for Geological risks

Legal frameworks also need to address liability for geological risks. Hydrogen can migrate, react with minerals or microbes, or leak through faults. However, unlike CO_2 storage where the EU CCS Directive clearly defines long-term liability and allows eventual transfer of responsibility to the state. UHS has no established rules for who is responsible if hydrogen escapes or contaminates groundwater. This is one of the biggest gaps preventing large-scale UHS deployment[41].

Legal Aspects	Summary
Land-use & subsurface rights	Ownership of pore space and stored hydrogen is unclear, varies by country.
Hydrogen's legal status	No consistent definition; treated differently across laws, causing regulatory confusion.
Permitting process	Permits are slow and inconsistent, with no dedicated UHS pathway.
Technical standards	Few hydrogen-specific standards exist, leading to uncertain safety requirements.
Geological & environmental risks	No clear rules for monitoring, leakage, or geochemical impacts.
Long-term liability	No framework for post-closure responsibility; operators may remain liable indefinitely.

Table 3.5: Legal aspects of UHS.

3.1.6 Environmental Aspects

Subsurface Risks and Hydrogen Migration

There are several subsurface environmental risks associated with Underground hydrogen storage, primarily related to hydrogen's high diffusivity, low viscosity, and strong mobility. Compared with methane or CO_2, hydrogen migrates more readily through porous media and can escape through microfractures, faults, or poorly sealed wellbores. Also, hydrogen's small molecular size increases the likelihood of leakage, especially in aquifers and depleted reservoirs where geological heterogeneity is significant [17]. Salt caverns, by contrast, exhibit extremely low permeability and are therefore considered the safest geological option for preventing hydrogen migration [44].

Hydrogen migration can also be influenced by geochemical and microbiological processes. In porous reservoirs, hydrogen can react with minerals or stimulate microbial activity, leading to methanogenesis or sulphate reduction. These reactions may reduce stored hydrogen volumes and generate by-products such as methane or H_2S, which pose environmental and safety concerns and therefore is a matter of concer). Such reactions are far less likely in salt caverns, where the geological medium is inert and lacks microbial populations[44].

Environmental Life-Cycle Impacts of UHS

A full environmental assessment of UHS requires a system-level life-cycle perspective, considering hydrogen production, compression, storage, withdrawal, and end-use Currently there's no dedicated studies on the LCA of hydrogen which considers UHS options hence assuming its effect on environment is not clear can be understood through separate environmental impact of UHS. Future LCA frameworks for hydrogen infrastructure must integrate geological storage impacts, including energy consumption for compression, cavern construction, and monitoring[45]

Life-cycle impacts vary significantly by storage type. Salt caverns generally exhibit lower operational emissions due to minimal leakage and stable thermodynamic behaviour. In contrast, porous reservoirs may require more intensive monitoring, leakage mitigation, increasing their environmental footprint. Additionally, the round-trip efficiency of hydrogen storage often below 40% when reconverted to electricity means that the environmental benefits depend heavily on the carbon intensity of the input electricity as in the form of hydrogen (green, blue, grey etc) [17], [44]

Water Requirements for Solution Mining and Brine Disposal

Salt cavern construction requires large volumes of freshwater for solution mining, which dissolves salt to create the storage cavity. This process can impose significant environmental burdens, particularly in arid regions where there is already water scarcity. For example, the 'Tuz Gölü' project in Turkey requires freshwater transported over long distances to support cavern leaching Such withdrawals may affect local water availability, aquatic ecosystems, and competing agricultural or municipal uses [44].

Brine disposal is another major environmental challenge. The leaching process produces concentrated brine that must be safely managed. In the ‘Tuz Gölü’ project, brine is discharged into the nearby Salt Lake, but this approach is only feasible where natural hypersaline basins exist. In other regions, brine disposal may require deep-well injection, evaporation ponds, or industrial reuse, each with its own environmental risks, including groundwater contamination or soil salinization [44].

Comparative Environmental Advantages of UHS

Despite these challenges, UHS offers several environmental advantages compared with above-ground storage or alternative large-scale energy storage technologies. Underground storage requires minimal land footprint, reducing surface disturbance and visual impact. It also avoids the material intensity associated with large battery systems, which require critical minerals and generate end-of-life waste.

Salt caverns provide a highly secure and environmentally stable storage environment. Their extremely low permeability minimizes leakage risk, and their geological stability reduces the likelihood of subsurface contamination[39], [44]. When paired with renewable hydrogen production, UHS can support deep decarbonization by enabling seasonal balancing of wind and solar energy, reducing curtailment, and lowering reliance on fossil-fuel-based backup systems [17]

Environmental Aspects	**Summary**
Subsurface risks & hydrogen migration	Hydrogen may migrate through faults or porous formations; salt caverns offer best containment.
Microbial & geochemical reactions	Hydrogen can be consumed by microbes or react with minerals in porous media, producing methane or H_2S.
Life-cycle environmental impacts	UHS has low land use and material intensity but requires energy for compression and monitoring.
Water use for solution mining	Large freshwater volumes needed to create salt caverns; site-specific sustainability concerns.
Brine disposal impacts	Brine must be safely discharged or reused; improper disposal can harm ecosystems.
Comparative advantages	High capacity, low surface footprint, and strong synergy with renewable energy systems.

Table 3.6: Environmental Aspect of UHS.

Figure 3.2: PESTLE analysis overview.

3.2 SWOT Analysis

3.2.1 Salt Cavern

Strengths

Technical Benefits

High Purity and Integrity

The technical advantages of salt cavern hydrogen storage primarily arise from their unique geological and engineering characteristics. The extremely low permeability and self-healing ability of salt rock layers create a natural sealing barrier, ensuring minimal hydrogen leakage even under high-pressure cycling conditions. Unlike porous reservoirs or aquifers, salt layers are chemically inert, which eliminates the risk of hydrogen contamination from reactions with host rock minerals or residual fluids. This guarantees the purity of hydrogen after long-term storage, thereby meeting the strict requirements of fuel cells and ammonia synthesis processes (which requires very high purity hydrogen) [46]. This avoids the significant operational expenditure (OPEX) associated with gas purification, a challenge often encountered in depleted gas reservoirs where geochemical and microbial reactions can contaminate the hydrogen with species like H_2S and CH_4 [47]. The inherent integrity of salt also minimizes gas loss through leakage, ensuring that the stored product retains its value.

High Injection and Withdrawal Rates

From an engineering perspective, the cavities formed through solution mining allow for operation at high pressures of 20–30 MPa. When combined with dynamic pressure regulation technology, this enables rapid injection and extraction of hydrogen, reducing response time and facilitating fast cycling for which multiple cycling is possible and that's what makes salt caverns economic [46].

Economic Viability

Even though Capex of Salt cavern could be significantly higher due to site development cost, repurposing depleted gas reservoirs, aquifers, or constructing above-ground tanks could sometime be even more expensive. Existing infrastructure, such as repurposed natural gas salt caverns, can reduce initial investments. For instance, the Clemens Dome project in Texas utilizes existing salt caverns originally designed for natural gas storage, resulting in a 40% reduction in development costs [46]. Due to the self-sealing properties of salt, operational costs are also minimized, greatly reducing the need for ongoing maintenance or leak monitoring. Furthermore, the scalability of salt caverns allows for phased expansions in response to the growing demand for hydrogen, avoiding large-scale initial investments. Compared to liquid hydrogen tanks, salt cavern storage can reduce the levelized cost of hydrogen storage (LCOHS) by 15% to 20% [48].

Environmental and Safety benefits

Salt caverns offer significant environmental and safety advantages, aligning with global sustainable development goals. Their impermeable nature virtually eliminates the risk of hydrogen leakage, which is crucial for mitigating climate change given the high global warming potential of hydrogen released into the atmosphere[49]. Unlike aquifer storage, salt caverns do not compete with freshwater resources and pose no risk of groundwater contamination, as the leaching process utilizes a controlled brine circulation system [50].

Weakness

Economic and Regulatory barriers

The economic viability of salt cavern hydrogen storage is hindered by high upfront costs and regulatory uncertainties. Although the solution mining method is cost-effective compared to other approaches, the development of new salt caverns in deep salt formations can exceed USD 50 million per project, with the leaching process alone accounting for 40-60% of the total cost [51]. Repurposing existing natural gas salt caverns can reduce costs; however, modifications are necessary to meet specific safety standards for hydrogen, which are inconsistently enforced across different regions [52]. The regulatory framework for hydrogen storage is still in its infancy, with many countries lacking clear guidelines on risk assessment, monitoring, or liability allocation. For instance, the EU's hydrogen strategy acknowledges the potential of salt caverns, but implementation is left to member states, leading to policy fragmentation that hampers cross-border investment [51].

Geographical Limitation

The formation of salt deposits suitable for creating large-scale storage caverns is a rare geological feature. These formations are confined to specific regions (e.g., the U.S. Gulf Coast, Northern Germany, parts of the UK and the Netherlands).

This creates a significant spatial disconnect, as these ideal storage locations are often far from the optimal sites for hydrogen production (e.g., areas with high solar or wind potential) and the major industrial or urban centers where hydrogen will be consumed. This geographical mismatch necessitates the construction of long-distance, dedicated hydrogen pipelines to connect production, storage, and consumption hubs. This infrastructure represents a massive capital expenditure (CAPEX) that can challenge the economic viability of a project. It also creates a dependency on a fixed infrastructure network, leading to potential stranded assets if energy demand centers shift in the future [53].

Opportunities

Policy Support & Financial Incentives

Governments worldwide are implementing robust policies to accelerate the transition to a hydrogen economy. Major legislative packages, the EU's Hydrogen Strategy under the Green Deal, have created powerful financial incentives. This strong policy landscape significantly de-risks private investment in large-scale hydrogen infrastructure. For salt cavern projects, this can translate into direct subsidies, investment tax credits, and streamlined permitting processes. These incentives lower the effective capital expenditure (CAPEX), improve the overall project economics, and make it easier to secure financing, thereby accelerating the development of hydrogen storage hubs[54].

Renewable Energy Integration

The rapid expansion of intermittent renewable energy sources, like solar and wind, creates grid instability and periods of massive energy surplus where generation exceeds demand. Salt caverns offer a solution by providing high scale, long-duration energy storage. By using excess renewable electricity to produce green hydrogen via electrolysis (Power-to-Gas), salt caverns can store this energy for weeks or even months. This stored hydrogen can then be used when renewables are unavailable, providing a reliable energy supply, balancing the electrical grid, and preventing the costly curtailment (waste) of renewable power. This symbiotic relationship makes renewable energy projects more profitable and enhances overall energy security, creating a strong business case for co-locating hydrogen production and storage with large renewable hubs[55].

Threats

Market & Price Volatility

The business case for large-scale energy storage relies heavily on price arbitrage-storing energy when it is cheap and selling it when it is expensive. The future market structure for hydrogen is still developing and highly uncertain. If the future hydrogen market has low volatility (i.e., a small price difference between peak and off-peak periods), the revenue generated from cycling the stored hydrogen may be insufficient to recover the facility's high capital and operational costs. This commercial risk can make the project unprofitable and unattractive to investors without long-term government subsidies or guaranteed offtake agreements, which may be difficult to secure [54].

Social and Environmental Concerns

The salt cavern hydrogen storage facility is not only a key infrastructure for the national energy reserve but is also closely related to the lives of enterprises and residents. When selecting a site, it is necessary to consider not only the local social acceptance, but also to comprehensively evaluate the local hydrogen energy policies and coordinate with the local hydrogen energy industry system to promote the development of the local hydrogen energy industry. Public acceptance and environmental impact present significant challenges to the expansion of salt cavern storage. The discharge of brine during the salt cavern leaching process raises ecological concerns, and improper management may lead to groundwater contamination or soil salinization. In densely populated or ecologically sensitive regions, land use conflicts may arise, and communities may oppose underground projects due to concerns about ground subsidence or explosion risks. Misunderstandings regarding hydrogen safety, such as the flammability range of hydrogen in air (4–75%), often overshadow its benefits, necessitating strong public engagement activities [46].

3.2.2 Depleted Reservoir

Strengths

Low Initial CAPEX

Depleted reservoir’s biggest strength is it’s low capex requirement. Reusing existing wells, surface facilities, and the reservoir itself drastically reduces upfront costs compared to creating new storage. This significantly lowers the barrier to entry and can lead to a much faster return on investment compared to salt cavern[56].

Vast Storage Capacity

These reservoirs are often very large and have a proven history of containing pressurized gas for millions of years. The large volume allows for economies of scale, lowering the per-unit cost of storage ($/kWh) and enabling the creation of large, strategic hydrogen reserves [56]

Weaknesses

Gas Contamination

Residual hydrocarbons and reservoir minerals can react with hydrogen, and resident microbes can consume it. This can contaminate the withdrawn hydrogen with species like methane (CH4) or hydrogen sulfide (H2S). This requires costly gas separation and purification plants, adding significant OPEX. It also poses a market risk, as the gas may not meet the high-purity standards required for fuel cells without expensive cleaning[56], [57].

High Cushion Gas Requirement

Due to the porous nature of the rock, a large volume of gas (a mix of native gas and injected hydrogen) is required as permanent cushion gas to maintain pressure. Usually, the cushion gas required for reservoirs are 50% to more which reduces the revenue amount significantly. A significant portion of the injected hydrogen is not recoverable, representing a large, permanent loss of valuable inventory[58].

Opportunities

Repurposing Stranded Assets

As the world transitions away from fossil fuels, depleted gas fields represent stranded assets. Converting them to hydrogen storage creates new economic value. This provides a compelling business case for oil and gas companies to transition their infrastructure and workforce, potentially attracting investment and government support for a just transition[58].

Threats

Well Integrity and Leakage

Old wells may have been designed for natural gas, not hydrogen. Seals and cement may degrade, creating potential leakage pathways. The risk of leakage is a major environmental and financial liability. The economic analysis must include the high cost of assessing, retrofitting, and monitoring old wells to ensure they are hydrogen-ready. Failure to do so could result in fines and loss of all stored product[57], [59].

3.2.3 Saline Aquifers

Strengths

Widespread Geographical Availability

Suitable saline aquifers are much more common globally than salt formations or hydrocarbon fields. This allows for the potential development of hydrogen storage closer to demand centers, drastically reducing the need for expensive long-distance hydrogen pipelines and lowering overall system costs[58].

Weaknesses

High Geological and Containment Uncertainty

Unlike depleted reservoirs, aquifers have no proven history of gas containment. The integrity of the caprock and potential for hydrogen to dissolve in brine or leak are major unknowns. This translates to extremely high exploration and site characterization costs, with no guarantee of success. The risk analysis must assign a high probability of project failure at the exploration stage, making it difficult to attract private investment without significant government de-risking[60].

Low Hydrogen Recovery Efficiency

Due to dispersion in the porous media and dissolution in the brine, a significant fraction of the injected hydrogen may be unrecoverable. This directly impacts revenue, as a large percentage of the stored product is lost. Financial models must use a much lower "round-trip efficiency" compared to salt caverns, harming profitability[61].

Opportunities

Enormous Storage Capacity

The potential storage volume in aquifers globally is immense, far exceeding that of salt caverns or depleted reservoirs. If the technical challenges can be overcome, aquifers offer a long-term solution for storing the vast quantities of energy required for a global hydrogen economy, representing a massive future market[58], [59].

Threats

Environmental Risks and Public Acceptance

Injecting large volumes of gas could displace saline water, potentially impacting local hydrology or causing induced seismicity. These risks are poorly understood which creates a significant regulatory and liability risk. The potential for unforeseen environmental damage could lead to costly legal challenges, project shutdowns, and a failure to gain public acceptance, making the project unviable [60].

3.2.4 Integrating PESTLE and SWOT

In order to get a better understanding of the PESTLE and SWOT, a combined analysis approach is useful where which of the PESTLE factors are considered either a Strength, Weakness, Opportunity or Threat can be identified. According to our analysis, Political, social and Technological factors can be considered as strength because of growing UHS policies, Govt. support and funding, Job market creation, Local benefits and technological improvements. Weaknesses include Technological, Environmental and political factors due to technological immaturities and challenges, environmental risks and lack of dedicated policies. Also, Social and political aspects could be considered as Opportunities as there are more awareness regarding renewable energy and increased R&D and support. Lastly, Economical and legal aspects could also possess threats toward UHS because of high infrastructure cost, lack of funding, no binding regulations and lack of standards.

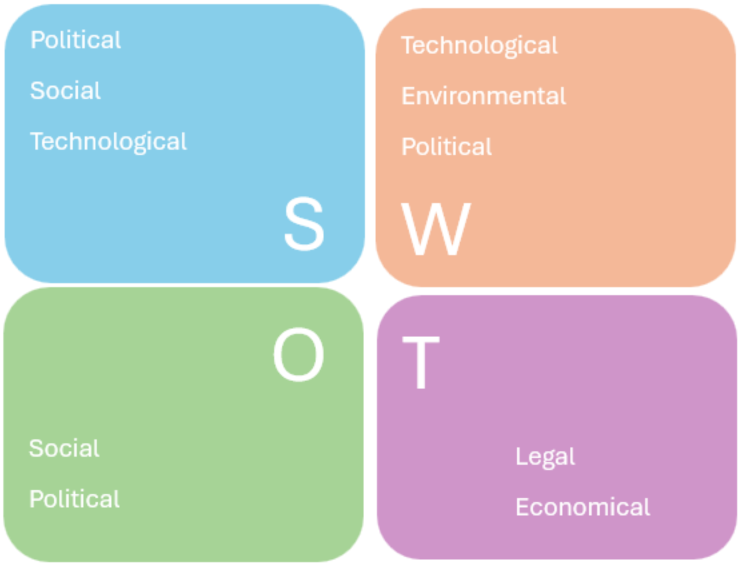

Figure 3.3: Integrated PESTLE & SWOT analysis.

3.3 Techno-Economic Analysis

Geological storage synchronizes supply and demand across time and locations in a cost-competitive way. Which means cost parameters can vary widely across locations and time and many other factors. For this study Two different hypothetical geological sites were assumed for the evaluation. A hypothetical salt cavern (Type A) and a porous reservoir (Type B). The reason to Choose a generalized porous reservoir over separated depleted reservoir and aquifer is for generalized assumptions, these two types have more similar cost figures (as in low capex, higher opex, cushion gas requirements etc). And the valuation framework is adapted from [22]Both geological storage receives sourcing gas from a ratable and responsive hydrogen supply, like a steam methane reforming (SMR) process with carbon capture and storage, for end markets like industry (chemical plants and refineries) and transportation. The value of storage is to have additional hydrogen to meet the demand for various demand patterns (seasonality and weekends) or to serve as a supply backup for security reasons.

3.3.1 Valuation Framework

The stakeholders for geological hydrogen storage asset include asset owners, value chain and market participants, and even communities near or served by the asset. Different stakeholders evaluate the same project with different yielding benefits and costs based on their perspectives and interactions with the asset. Three analytical components constitute the valuation framework in the current study and provide analytical reference to all three types of stakeholders.

- Techno-economic analysis (TEA) focuses on the capital cost components and operating cost assumptions for a stand-alone asset.

- A value chain scenario describes the operating schedule and requirements for the asset, including assumptions about the upstream pathway and pattern for injection and withdrawal requirements for the downstream user. This step describes the volume and utilization of the asset.

- The net present value (NPV) model combines the utilization, cost, price (market perspective), and finance theory to calculate the asset's cash flow throughout its lifetime, risk adjusted discount rate and estimate the assets' value and rate of return. The NPV model acts as the framework's last step, integrating the cost, economic, risks, and market perspectives into one value.

The market conditions and assumptions are crucial to both TEA and the NPV model in three ways. First, the assumption of the flow rate and capacity of the upstream hydrogen supply (for example, the capacity of an electrolyzer or the flow rate of an SMR plant) directly determines the injection capacity required for the storage project. Second, the downstream application's demand seasonality and volume determine the withdrawal capacity requirement. For example, if the storage project is serving a turbine for generating electricity sold to the grid, the withdrawal capacity of the storage is determined by the generation capacity of the turbine. At last, the working gas capacity of the storage asset is also determined on the basis of the estimated range of inventory given the interaction between injection and withdrawal over time. Assumptions about the working capacity of storage and the deliverability (injection and withdrawal) requirement then influence both the capital expenditure (CAPEX) and operating expenditure (OPEX) of the plant. For example, the storage facility's sizing for its pipeline size, casing, cavern size, and compressor capacity must be aligned with the capacity requirements. The capacity requirement then determines the operational limits and cycles of the plant, hence the revenue stream in the NPV model.

TEA

The techno-economics model's basic components of capital costs include pipeline, well, site, solution mining (for salt cavern), and compressor. This study has included updated assumptions and data points from literature [19], [21], [22]For each capital component to reflect more realistic values. The storage asset may be collocated with other assets, like a hydrogen production source or a downstream application of hydrogen. Together with hydrogen storage, these assets form an energy system, which often determines the operation and utilization requirement of the storage asset. It is essential to note that the cost estimates and valuation analysis in this research only consider the storage asset itself, not production or distribution.

CAPEX and OPEX assumption:

The range of costs for well construction and solution mining varies greatly depending on the specific development conditions and plans; well construction and solution mining make up the majority of the total CAPEX of the project. One other factor in site development is cushion gas, which is purchased and stored in the cavern. Assuming integrity sufficient for the salt cavern to store hydrogen, the cushion gas can be recovered at the end of the project life. Therefore, this study considers the cost of cushion gas part of the working capital instead of the capital investment. The cost of well and site development, compressor is adapted from literature based on the capacity assumed.

Price spread between withdrawal and injection prices

The economic valuation of a storage facility is a function of the price spread between injection and withdrawal, where the storage enables the ability to carry the product, hydrogen in this example, through time, hoping to take advantage of price fluctuation in the future market. One common scenario is to consider an independent player that inject hydrogen at low prices, stores it and sells it when the price is higher, often along with periods of higher demand. The price spreads indicate the different price levels across time, between withdrawal and injection. This difference is reflected as seasonal demand pattern, like winter prices versus summer prices for transportation fuel sector.

Net present value and discount rate

Across literature LCOE is the most common method used to evaluate UHS projects. Levelized cost of energy has been historically utilized in the preliminary cost analysis for energy-producing projects and technologies with a measurement metric of cost per unit of energy produced. The main purpose of LCOE is to demonstrate and compare the average overall cost required to produce one unit of energy, equivalent to determining the minimum revenue required per unit of energy produced to cover the unit cost. The criteria for a company's manager to accept an independent project is that the project's LCOE can be covered by selling each unit of energy to the market.

But instead, this work establishes a comprehensive NPV model to evaluate geological hydrogen storage. The NPV model uses a scientific and fundamental cost-benefit analysis to conduct capital budgeting. It accounts for the time value of money, all the cash flows generated from the project, project risk, and cost of capital. When NPV is greater than zero, it means that the project will add value to the firm.

With the NPV framework, how NPV is changed with discount rate can be analyzed. The higher the discount rate, the less the value of NPV. The discount rate which leads to zero NPV, is called the international rate of return (IRR). IRR is the highest return that can be received from the project. With IRR criterion, managers should only accept a project when the project's IRR is greater than the cost of capital.

The NPV equation follows:

$$NPV = \frac{FCF_0}{(1+i)^0} + \frac{FCF_1}{(1+i)^1} + \cdots + \frac{FCF_N}{(1+i)^N} \quad \text{...Equation (1)}$$

In Equation 1, N is the project life, i is the discount rate, and FCF is free cash flow. FCF_0 is the initial investment, including initial CAPEX and the initial net working capital (NWC) tied to the project.

The established NPV model projects the benefits (revenues) that will be generated from the hydrogen storage and all the costs that will occur including CAPEX, OPEX, tax liabilities, etc., and then calculates the free cash flow, the discounted present value of all the future cash flow, and NPV. Free cash flow is calculated as follows:

$$FCF = EBIT \times (1 - Tax\ rate) + Depreciation - (Change\ in\ gross\ fixed\ assests + Change\ in\ net\ working\ capital)$$ ...Equation (2)

Where: $EBIT = Revenue - Expenses - Depreciation$

Assumptions

The following assumptions are made for the hydrogen geological storage NPV model.

- The project has a 30-year lifespan.
- One compressor will be used. The compressor has a 20-year lifespan; the initial compressor will need to be replaced in year 20. The after-tax salvage value of the second compressor is captured at year 30.
- The well has a 30-year lifespan.
- The storage site has a 40-year lifespan, and its after-tax salvage value is calculated at year 30.
- Construction is completed in year 0, and production starts from year 1 (if there is construction after year 0, it can be discounted back to year 0).
- At the end of the equipment life, the equipment salvage value is 10% of the equipment cost. If the project ends before the equipment's life, the salvage value is assumed to be the same as the equipment's remaining book value.
- Straight-line depreciation is applied for the fixed assets.
- Cushion gas cost is considered NWC, which will be recovered by the end of the project life. Other NWC is set as 10% of next year's revenue.
- The weighted average cost of capital (WACC) is used as the discount rate for FCF.

Site design characteristics	Salt cavern	Depleted reservoir
Formation Pressure, kPa	13,890.87	13755
Formation temperature, °K	310.9	315.1
Formation depth, m	1158	1403
Cavern volume, m^3	580,000	676,941
Working gas, (kg H_2)	6,212,425	6,212,425
Cushion gas percentage of total volume	30%	50%
Cushion gas, (kg H_2)	1,863,727	3,106,212
Total H_2 stored, (kg H_2)	4,348,697	3,106,213

Table 3.7: Site characterization assumptions (adapted from[22])

Market scenario for sites

The scenario is single-turn salt cavern and Porous reservoir storage project serving the seasonal peak demand of the transportation sector. The scenario assumes the existence of a local market of the transportation sector for hydrogen similar to one for city transportation [21]This scenario requires the storage of hydrogen for four months (120 days).

For the source of hydrogen, this scenario assumes a steady rate of injection for the rest of the year (230 days), which can be a purchasing agreement tied to a local hydrogen production source, like a steam reforming plant, at a fixed price of hydrogen. The storage asset can only inject or withdraw, not do both at once. Given the market assumption, this storage site has:

- A total working capacity of 6,212,425 kg/yr of hydrogen, with 30% cushion gas for the salt cavern and 50% for the reservoir.
- Injection capacity of 1125 kg/h (equivalent to 11.2 MMSCF/ d) of hydrogen for 230 days; withdrawal capacity is 2157kg/ h of hydrogen for 120 days (equivalence to 21.5 MMSCF/d).
- The injection price of hydrogen here is about €1.30/kg, based on the levelized cost of hydrogen from a steam reforming process with carbon capture storage, with natural gas, electricity and water.

Cost assumptions		Salt Cavern (A)	Porous reservoir (B)
Capital cost	Pipeline, €	-	-
	Well cost, €	15,349,000	15,349,000
	Compressor (year 0), €	5,544,370	5,544,370
	Site development (excluding cushion gas), €	33,982,125	10,000,000
	Total capital cost at year 0, €	54,875,495	30,149,069
Initial net working Capital	Cushion gas, €	2,394,062	4,038,076
	Other NWC, €	1,799,694	1,799,694
	Total NWC, €	4,193,756	5,837,770
Operating cost	Compressor O&M on electricity, €/kgH2	0.10	0.10
	Compressor O&M on water and cooling, €/kgH2	0.01	0.01
	Well O&M, % of well CAPEX	4%	4%
	Dehydration, € /kgH2	0.0034	0.0034
	SGA: Sales and General Administration Expenses, % of revenue	1%	1%
Lifetime	Site, years	40	40
	Pipeline, years	30	30
	Well, years	30	30
	Compressor, years	20	20
	Project performance, years	30	30
Salvage value	Salvage value at the end of project	10%	10%
Tax	Corporate tax rate	25%	25%
Discount rate	WACC	9%	9%
Result			
Injection price	€/kg	1.3	1.3
Withdrawal price	€/kg	3.42	3.42
Total initial investment	€	59,698,422	35,986,839
NPV	€	47,541,697	16,956,367
IRR		18%	12%
Profitability Index	%	1.79	1.49
Payback period	Years	8	10

Table 3.8: Cost modelling assumptions [19], [21], [22].

Notes:

Site development capital costs cover capital costs of cavern solution mining, cavern de-brining, and brine utilization. Well capital cost covers capital costs of surface filtering, drying, heat exchange, and metering units. (Adapted from [22]

a. All costs and prices are in year 2025 real Euros.

b. No last-mile pipelines are included in these scenarios.

c. Single well; 13.375-inch casing for Site B, and 20-inch casing. Piping, gas handling, purification, and dehydration units are included.

d. Power requirement is 2623 kW with compressor unit cost of €2130/kW.

e. Site development includes solution mining plant (1000 gallons per minute), piping, and drilling water wells for Site A; and water purchase and disposal fee for Site B.

f. Hydrogen is used for cushion gas and is assumed to cost €1.30/kg. Cushion gas is treated as working capital and sold at the end of the project.

g. 10% of the first year's revenue is assumed as working capital.

h. Injection price assumption is based on the LCOE of hydrogen from steam reforming with carbon capture and storage (CCS).

i. Withdrawal price is an indicative market price of hydrogen competitive cost of hydrogen lower bound of €3.4/kg [22].

4 Results and discussions

The results of the analysis are presented in this chapter, together with a description of the findings and a summary of their implications.

4.1 Results

Results from the established net present value (NPV) framework

The table provides both hydrogen storage assets' cost breakdown and NPV results, including initial capital investment (CAPEX), initial net working capital required, and the total initial investment. The NPV of site A is €47, 541, 697, and the NPV for Site B is €16, 956, 367. The positive NPV results show that hydrogen storage will add value to the company, and thus it will increase shareholders' wealth. Positive NPV results meet the capital budgeting criteria for investors to take the hydrogen storage projects. The NPV framework can also calculate the internal rate of return (IRR), which is the highest return from the projects. Both sites have IRRs greater than cost of capital, meeting the criteria for the project to be economically viable. In the meantime, it is also prominent that, despite of having a lower CAPEX, site B has a lower PI and higher Payback period than site A which implies that porous reservoirs are less economically suitable than salt cavern.

		Site A	Site B
Total initial investment	€	59,698,422	35,986,839
NPV	€	47,541,697	16,956,367
IRR		18%	12%
Profitability Index	%	1.79	1.49
Payback period	Years	8	10

Table 4.1: Results highlights

Financial metrics comparison between two sites

From the results highlights, the absolute difference between the NPV of two projects calculated is €30,585,330; Site A creates about €30.6 million more value than site B at the chosen discount rate. Which implies site A's NPV is about 2.8 times that of site B, or roughly 180 % higher NPV.

4.2 Risk Analysis

A comprehensive risk assessment has been done to further evaluate the economic framework through a sensitivity analysis of NPV and IRR for both storage sites. In business practices, the valuation of an asset based on the techno-economics and net present value cash flow model not only provides one estimate, but more importantly a consistent approach to assess risks around the valuation results or compare different scenarios and assets. And this is also where our previous PESTLE and SWOT analysis comes into play. For the sensitivity analysis the parameters considered are the ones assumed to have the greatest effect on the cost model which was discussed in details during the PESTLE and SWOT analysis.

Based on the NPV models of both storage assets, a sensitivity analysis of five variables, with a range of ± 20%, reveals the range of impacts on the valuation results, specifically in terms of NPV and IRR. The results are presented in tornado charts that rank price spread and costs from the greatest to the least. The 20% range was considered because as discussed in PESTLE, the corporate tax doesn't have a fixed valuation in EU and rather varies between a wide range of 20%-30% and so is the value of WACC which also varies between 6%-10% and the price of hydrogen varies within a broader range as well; hence analyzing over a 20% range gives a proper insight on the cost model and its future scenarios if the value increases or decreases.

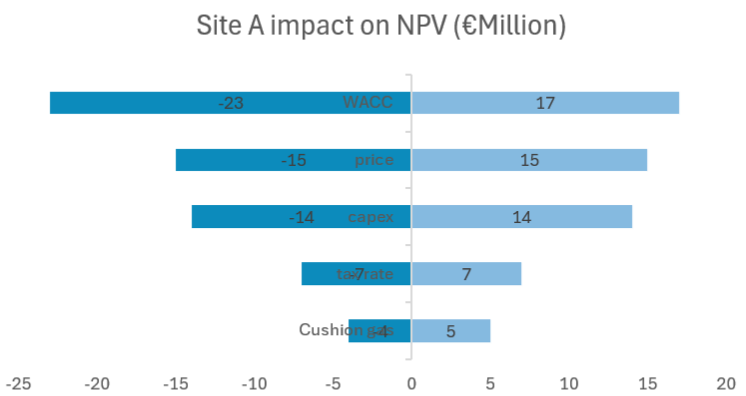

Figure 4.1: Site A NPV

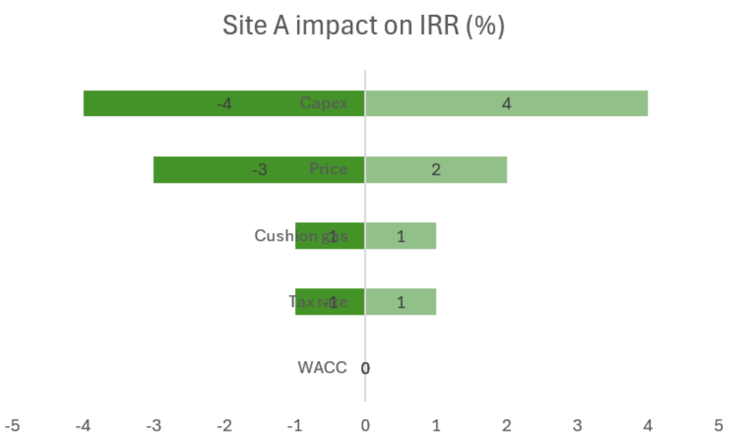

Figure 4.2: Site A IRR

From the figures, For site A, The top driver is the WACC for NPV which means discount factor is a core value driver for a UHS project followed by price spread and capex value of the project. This provides insights that hydrogen price and capex are crucial for the deployment of a project. However, IRR shows slightly different pattern which is understandable as it depends solely on the FCF hence being most affected by capex and price spread.

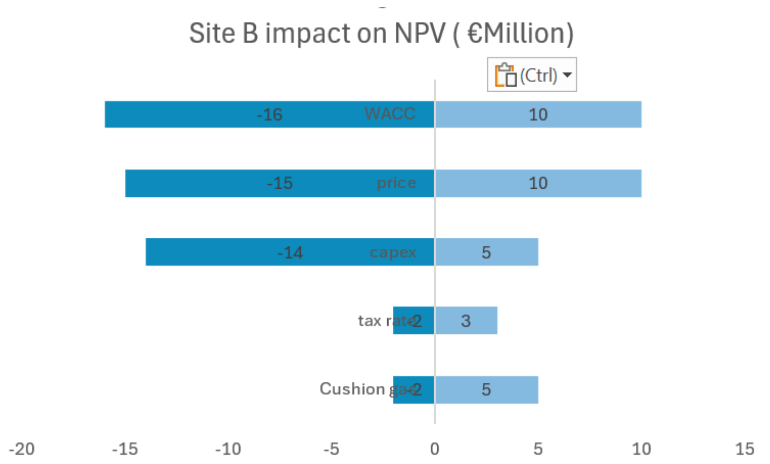

Figure 4.3: Site B NPV

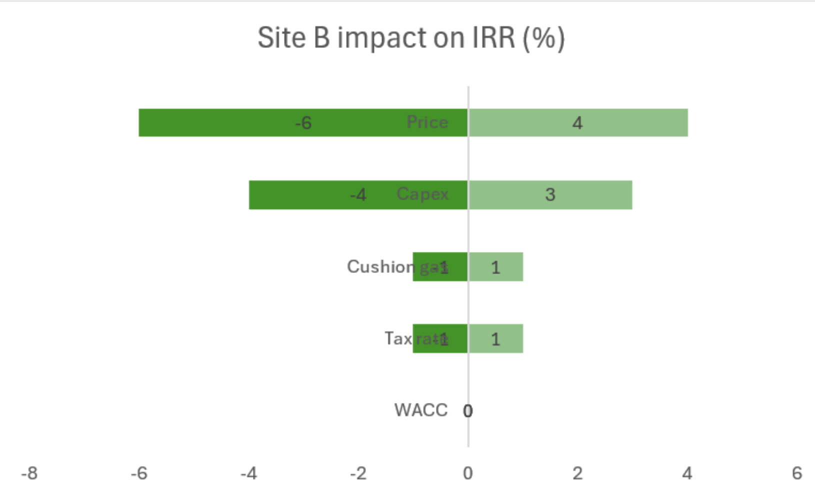

Figure 4.4: Site B IRR

For site B, we see a similar pattern with only slightly different numbers, where WACC accounts for most impact on the NPV followed by price spread and capex, while tax rate and cushion gas has their impact but that is less than WACC and capex. And again a similar pattern for IRR is observed for site B. This sensitivity analysis implies that porous reservoir; despite of having lower capex is simply affected similarly by the cost driving parameters.

However, Comparing the sensitivity analysis of two sites, site A definitely shows more sensitivity towards varying economic factors than site B mostly for the NPV which implies the risk associated with that as in if WACC decreases we can get higher NPV for site A in comparison to site B but for the opposite scenario the NPV of site A would decrease more than site B.

4.3 Discussion

This thesis adopted a multi-layered analytical framework to evaluate the strategic viability of Underground Hydrogen Storage (UHS) across diverse geological settings.

The initial classification of UHS sites into salt caverns, depleted gas reservoirs, and aquifers provided a foundational lens for technical and operational comparison. Salt caverns emerged as the most mature and commercially proven option, offering high withdrawal rates, low permeability, and well-understood engineering protocols. Depleted gas reservoirs, while offering large volumes and existing infrastructure, presented greater uncertainty in terms of hydrogen migration, microbial activity, and long-term containment. Aquifers, though abundant and geographically widespread, remain the least developed and most geochemically complex option, requiring further research into hydrogen-rock and hydrogen-microbe interactions.

This classification enabled a functional assessment of each storage type’s behaviour under hydrogen-specific conditions, including cushion gas dynamics, injection and withdrawal performance, and subsurface integrity. The comparative analysis highlighted that geological suitability alone is insufficient for deployment decisions; broader systemic factors must be considered.

The PESTLE analysis provided a structured evaluation of macro-environmental factors shaping the feasibility and resilience of UHS projects. Politically, the alignment of national hydrogen strategies with EU decarbonization goals was found to be a key enabler, particularly in countries with existing underground gas storage infrastructure. Economically, the volatility of hydrogen pricing, the cost of electricity for electrolysis, and the capital cost of cavern development emerged as critical variables influencing project bankability.

Social acceptance was identified as a latent risk, especially in regions unfamiliar with subsurface energy infrastructure. Technologically, the absence of hydrogen-specific standards and monitoring protocols was a recurring barrier, underscoring the need for regulatory innovation. Legally, the lack of harmonized EU directives for hydrogen storage created uncertainty around permitting, liability, and subsurface ownership. Environmentally, the analysis revealed both risks (e.g., brine disposal, water use in solution mining) and benefits (e.g., low surface footprint, synergy with renewables), reinforcing the importance of site-specific environmental assessments.

The SWOT analysis complemented the PESTLE framework by identifying internal capabilities and external pressures for each storage category. Salt caverns demonstrated strong technical reliability and scalability, but their geographic limitation and high water demand for solution mining were notable weaknesses. Depleted reservoirs offered infrastructure reuse and large capacity, but faced challenges in monitoring, leakage risk, and regulatory ambiguity. Aquifers presented long-term potential due to their widespread availability, yet their uncertain geochemical behavior and lack of operational precedent positioned them as a high-risk, exploratory option.

Opportunities across all categories included integration with renewable hydrogen hubs, alignment with EU hydrogen backbone initiatives, and potential for seasonal energy balancing. Threats included regulatory delays, market fragmentation, and competition from alternative storage technologies such as ammonia or LOHCs.

The final phase of the thesis developed a techno-economic model to evaluate the financial viability of UHS projects under varying input assumptions. The model incorporated capital costs (site development, well infrastructure, cushion gas), operational expenditures (electricity, water, maintenance), and market parameters (price spread, tax rate, WACC). Sensitivity analysis revealed that price spread and WACC were the most influential variables affecting Net Present Value (NPV), followed by site development costs and tax rate.

By comparing Site A and Site B under identical economic conditions, the model demonstrated how geological and infrastructural differences translate into financial outcomes. Site A, with higher upfront costs but better withdrawal performance, showed greater sensitivity to market conditions. Site B, with lower capital intensity but reduced scalability, offered more stable returns under conservative assumptions. The model thus provides a decision-support tool for investors and policymakers to identify optimal storage strategies based on risk tolerance, market dynamics, and long-term system value.

The integrated framework combining geological classification, PESTLE and SWOT analyses, and economic modelling offers a robust basis for evaluating UHS deployment. It reveals that successful implementation depends not only on subsurface suitability but also on policy alignment, regulatory clarity, economic incentives, and environmental safeguards. As hydrogen systems evolve, such multi-dimensional assessments will be essential to guide strategic investment and ensure that underground storage plays a central role in enabling a clean, resilient energy future.

5 Sustainability Analysis and Ethical Implications

From sustainability perspective, the amount energy used to conduct the analysis is taken into account based on equipment power consumption, so that amount GHG can be expressed as per European Union policies and more specifically country Spain’s policy.

Amount of CO_2 equivalent generated is calculated based on the amount of CO_2 per kWh which is 237 grams in EU and 146 grams in Spain. For this study every calculation is based on carbon intensity of Spain. The work type being entirely theoretical/analysis based, there are no other equiment cost included.

Equipment	**Working hours(hrs)**	**Energy (kWh)**	**CO_2(kg)**
Personal Laptop	400	28.40	4.15

The total estimated amount of CO2 equivalent released from utilizing the facilities during the project is 4.15 kilograms.

6 Conclusion and Further Work

6.1 Conclusion

This thesis presents a systematic and practical framework for evaluating the feasibility, strategic value, and economic performance of Underground Hydrogen Storage (UHS) across different geological settings. The study addresses a clear research gap by integrating geological assessment, macro-environmental analysis, and techno-economic modelling to understand how storage site characteristics influence long-term hydrogen system reliability. The findings contribute not only to academic understanding but also to the broader pursuit of safe, scalable, and resilient hydrogen infrastructure, which is essential for Europe’s transition toward sustainable energy systems.

To establish a foundation for this evaluation, UHS sites were classified into salt caverns, depleted reservoirs, and aquifers based on their geological properties and operational behaviour. This classification enabled a structured comparison of their suitability for hydrogen storage, highlighting the distinct advantages and limitations of each formation. The subsequent PESTLE analysis provided insight into the external pressures shaping UHS deployment, while the SWOT analysis revealed internal strengths and vulnerabilities that influence strategic decision-making. Together, these analytical layers offered a comprehensive understanding of how geological, regulatory, technological, and environmental factors interact to determine storage feasibility.

The development of a techno-economic model further strengthened the study by quantifying the financial implications of UHS deployment. Sensitivity analysis demonstrated that variables such as WACC, price spread, and capital intensity exert the greatest influence on Net Present Value, underscoring the importance of financial conditions and market design in determining project viability. This modelling approach provides a robust framework for identifying optimal storage strategies and supports informed investment planning for future hydrogen infrastructure.

The results of this thesis also emphasize the importance of addressing uncertainties in both geological behavior and economic performance. Hydrogen storage in porous media involves complex interactions-such as geochemical reactions, microbial activity, and pressure dynamics-that require careful evaluation. By combining qualitative and quantitative methods, the study demonstrates how multi-criteria assessment can capture these uncertainties and guide safer, more reliable system design. This approach is particularly relevant as hydrogen infrastructure expands and the need for long-duration, large-scale storage becomes increasingly critical.

In conclusion, this thesis contributes a structured and interdisciplinary framework for evaluating UHS options, offering insights that are valuable for policymakers, developers, and researchers. The findings highlight the need for coherent regulatory frameworks, rigorous site characterization, and economically optimized project design to ensure that underground storage can support the emerging hydrogen economy. By examining the interplay between geological suitability, external drivers, and economic performance, the study provides a foundation for future research and development, helping to ensure that hydrogen storage infrastructure is not only technically viable but also safe, reliable, and aligned with long-term sustainability goals. This work ultimately supports broader efforts to transition toward cleaner energy systems by ensuring that hydrogen storage solutions are robust, resilient, and strategically deployed.

6.2 Limitation and Further work

Even though this study provides sufficient insights into the economic and cost structure of UHS storage sites, however, there are several limitations to the study. UHS is an emerging technology, and a lot of assumption might not be the same when a project rolls out. Also, Due to the scope of the study it was not possible to rigorously analyse some factor or take them into consideration. Therefore, the study is limited in nature, with several critical research gaps that need to be addressed in the future as well. This section provides additional work recommendations to address the constraints of the existing thesis.

There is a need for more detailed geochemical and microbiological studies in porous media. Current understanding of hydrogen-rock and hydrogen-microbe interactions remains limited, particularly in aquifers and heterogeneous reservoirs. Future research should incorporate reactive transport modelling and long-duration laboratory experiments to better quantify storage performance and long-term containment.

The regulatory dimension requires deeper exploration. Many countries lack hydrogen-specific permitting pathways, liability rules, and monitoring standards. Future work should examine comparative regulatory frameworks and propose harmonized guidelines that reflect hydrogen's unique properties. This is especially important for cross-border hydrogen networks envisioned in Europe.

The economic model developed here can be expanded to include dynamic market conditions, such as fluctuating electricity prices, hydrogen demand growth, and carbon pricing trajectories. Different scenarios could be analysed other than the seasonal storage of hydrogen. Also, incorporating stochastic modelling or Monte Carlo simulations would allow for more robust risk assessment under uncertainty.

Also, environmental impacts; particularly water use and brine disposal in salt cavern development deserve more granular assessment. Future studies could explore alternative brine management strategies, including industrial reuse or mineral recovery, to reduce environmental burdens.

Finally, integrating UHS into broader energy system models would provide insights into its role alongside other storage technologies, renewable generation, and hydrogen carriers. Coupling UHS with sector-coupling models or hydrogen backbone simulations could help quantify its contribution to system flexibility, decarbonization, and energy security.

7 Economic Analysis

In this section, cost quantification of the research project is presented.

The work type being entirely theoretical/analysis based, there are no other equiment cost included.

Activity/Equipment	Working Hours	Cost/hr (€)	Total Cost (€)
Supervisory	32	40.00	1280.00
Research	450	15.00	6750.00

The total estimated cost of the project is 8030 Euros.

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Appendices