

# HYDROGEN TCP-TASK 42

## UNDERGROUND HYDROGEN STORAGE

TECHNOLOGY MONITOR REPORT 2023



## Colofon

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Hydrogen TCP-Task 42

# UNDERGROUND HYDROGEN STORAGE

**Technology Monitor Report 2023**

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## Foreword

In 2022 the Hydrogen Technology Collaboration Program approved to start up a new international task, known as TCP-Task 42, on storage of hydrogen in underground geological formations (UHS). Currently 54 participants from industry, universities, research organizations and governmental background have joined forces to seek synergies and opportunities for researching the main technical and economic challenges of UHS, which will help to advance towards demonstration in a full operational environment and to establish expertise and guidelines for all stakeholders involved.

There are a few experiences with pure underground hydrogen storage at several operational sites within the United States and the United Kingdom. Despite these commercial developments, it is clear that the technology is not ready yet for a full industrial and national scale implementation within the rapidly changing and decarbonizing energy system. The Hyunder Project (2012 – 2014) was one of the major flagships providing an integral investigation of the key challenges for a full-scale implementation of UHS. At that time, UHS was still regarded with moderate interest and only few nations considered it as a serious option for near future development. The drastic increase in ambitions for rapid upscaling of renewable energy and decarbonization solutions has also resulted in a global emergence of concrete development plans for large-scale energy storage solutions including UHS.

Over the past 5 years there has been a strong increase in research projects and studies investigating the feasibility and operational conditions of UHS in different subsurface settings. There is a wealth of new information and insights which now need to be demonstrated in a real environment. In this first TCP-Task 42 report we have compiled these insights based on the expertise and experiences of all participating experts involved. From this overview we have formulated several key actions and recommendations which will pave the way for a safe and responsible implementation in the coming years.

During the last year there have been many occasions in which TCP-Task 42 experts have shared their knowledge and discussed insights and challenges on underground hydrogen storage. Besides many online workshops, there have been several events with industry, universities and governmental stakeholders. These events and interactions have greatly contributed to the presentation of the state-of-art and remaining challenges.

We hope this Technology Monitor Report provides you with the answers you are looking for.

## Executive Summary

With the projected increasing demand for hydrogen generated by low-carbon and net-zero renewable energy production technologies, it is also expected that there will be a growing need for large-scale storage options for hydrogen. Such options will be needed, among others, to balance fluctuations in energy supply and demand at daily to seasonal time scales, and to strategically secure access to energy should major supply routes become disrupted.

The scale of future hydrogen storage demand is still uncertain, yet global forecasts estimate required storage volumes in the order of 580 – 650 bcm, surpassing the present-day operational volumes for underground natural gas storage (Chapter 1). Forecasts for Europe reveal a similar trend and such volumes can only be practically realized in deep underground formations such as salt and rock caverns, or porous rock reservoirs including depleted gas fields and saline aquifers. These options are summarized under underground hydrogen storage (UHS).

UHS has many technical similarities to underground natural gas storage. The same types of underground reservoirs and comparable principles are considered for exploration and storage operations. Despite these similarities, there are also profound differences in the way hydrogen behaves in the subsurface compared to natural gas, and how this behaviour may affect the safety, sustainability, efficiency and commerciality of UHS deployment and operations.

The implementation of UHS in the energy system context is still waiting for large-scale pilots and demonstration projects, which are essentially needed to resolve essential knowledge gaps and to validate experimental insights from laboratory and numerical modelling research in a real and full-scale subsurface environment. Such projects are also needed to build up industrial experiences, evaluate viable business case concepts and familiarize stakeholders and public with the advantages and implications of UHS.

This report is established by experts participating in the Hydrogen TCP-Task 42 community. It assesses the current state-of-art for UHS and provides key actions to enable UHS implementation including what is expected from pilot and demonstration projects. Besides the geological challenges, which focus on geochemical and microbial processes, storage integrity, storage performance, and site screening and ranking, the report reviews the latest engineering concepts for wells, surface facilities, monitoring and HSE. Some general insights are provided on the economic aspects of UHS, and a systematic approach is introduced to establish the UHS-related social aspects and thereby raise the societal embeddedness of this technology.

In summary the following findings and recommendations are reported per main theme.

### **Geochemical and microbial processes**

Hydrogen is a highly reactive element, which is likely to undergo or trigger geochemical and microbial reactions in the subsurface reservoir. There are indications that such reactions may occur both in salt caverns and porous rock formations. The latter is generally considered to be the most challenging setting due to the more complex and heterogeneous mineralogical and fluid composition and inherent uncertainties regarding reaction processes. It is essential that the current experimental knowledge on the occurrence and impacts of geochemical and microbial reactions is expanded by in-situ and field-scale observations resulting from pilot and demonstration projects in multiple geological environments and operational conditions. Specific emphasis is put on the quantification of coupled and interacting processes in a complex dynamic environment. The prediction and quantification of these processes can be improved by public databases, standardized best practices and monitoring instruments for testing, sampling and performing analyses.



### **Storage integrity**

There is ample experience with the safe and effective injection and containment of natural gas in porous rock formations and salt caverns. Experiences from industry-scale storage projects have proven that pure hydrogen can be effectively contained in salt caverns under low-frequency cyclic loading conditions. In order to confirm safe operational limits for fast-cyclic loading in salt caverns with hydrogen, further experiences must be gained from real cavern storage projects. This concerns permeation and progressive penetration of hydrogen into the cavern wall damage zone and potential non-halite interbeds and the effects of storage and cavern design and operations on the rock salt mechanical behaviour of a cavern over the entire life cycle.

Laboratory experiments and modelling work conclude that shale caprocks on top of porous rock formations can act as effective seal for hydrogen. Quantitative experimental work and modelling studies are needed to assess leakage through fractured clay-rich rock and the potential impacts of geochemical reactions on caprock integrity as well as the effective diffusion and dispersion of hydrogen in shaley caprock.

Most knowledge on cyclic stress-regime impacts on fracturing and fault slip comes from underground natural gas storage projects. There is limited experimental data on the impact of hydrogen on reservoir rock mechanics and on the impacts of fast cyclic loading and unloading with rapidly alternating high pressure variations which are typical to UHS operations. Further quantitative experimental and modelling studies, together with field monitoring data, should include different rock types and realistic reservoir conditions to increase understanding of reservoir stability and fracture generation. This includes among others the effects of mineral precipitation and dissolution on subcritical crack growth, progressive fatigue of reservoir rock due to intergranular clay swelling/shrinkage cycles and increasing slip-tendency due to geochemical alteration of the fault zone in presence of hydrogen. Special attention is needed on assessing heterogeneities and uncertainties in field-scale operations.

### **Storage Performance**

The many existing operational underground natural gas storage facilities in porous reservoirs and salt caverns provide valuable analogues to assess storage performance and model dynamic behaviour of hydrogen and other gases. The main differences result from the expected requirement of higher withdrawal/injection rates and cyclicity to match fluctuating demands. Another difference results from the impact of chemical and physical properties of hydrogen on reservoir performance. There is a need for further improvement of multi-scale models for hydrogen transport in porous reservoirs. Such models must be validated with experimental and real field-scale testing and monitoring measurements across different scales, geological settings and operational conditions in order to increase their reliabilities. Moreover, sensitivity analyses for quantification of the most influential parameters on the reservoir performance, considering field-scale heterogeneities and uncertainties, is crucial.

### **Storage facilities and wells**

Underground hydrogen storage facilities follow similar concepts for their design, construction and operations as being used for typical underground natural gas storage facilities. There are, however, many questions and knowledge gaps regarding the adaptations needed for the individual facility components and wells and to what extent existing wells and components will be suitable for a safe and effective operation with hydrogen. Specific solutions and concepts need to be developed to ensure the suitability, functionality, and resilience of applied materials and facility component designs to hydrogen and its potential reaction products. This also extends to the applicability and possibly required modification of existing facilities and legacy wells when converted for UHS operations. Adequate monitoring techniques must be developed to detect leakage as well as integrity issues occurring in the facility and wells. Purification technologies are key to meet the hydrogen quality criteria of the hydrogen transport net and end-users.

### Economics

Current mature experiences with salt cavern development and storage operations allow for a fairly reliable estimation of capital expenditure (CAPEX) and operational cost (OPEX) estimates. For UHS in porous reservoirs the uncertainty of cost estimation is still substantial, notably due to gas treatment and other measures and solutions that are needed to mitigate impurities in the hydrogen extracted from the storage reservoir. Project development costs are highly site-specific and new sites require substantial exploration and maturation efforts. It is therefore recommended to identify and establish approaches to reduce uncertainties and investment risks early on in the project. By building experiences from multiple projects, the reliability of costs estimates and potential economic gains from UHS will increase. Given the current absence of a market that supports commercialisation and upscaling of UHS, there is a need to assess market conditions for generating long term revenues, determine reasonable state-regulated prices/revenues for UHS and establish market regulation frameworks and conditions for early development projects and demonstrators.

### Societal embeddedness of UHS

The successful deployment and upscaling of UHS will strongly depend on whether the essential social aspects are defined and implemented. These aspects can be grouped in four main dimensions being i) environmental impact assessment, ii) involvement of stakeholders and public, iii) policy and regulations, and iv) market and financial resources. In this report, a systematic framework and methodology is presented to assess the current level of societal embeddedness in each dimension, and to benchmark these levels against the required societal embeddedness level that is needed to proceed technical development. It is recommended to test, expand and apply this framework and methodology in real UHS projects, together with assessment in a national context. The development of UHS may be accelerated by sharing experiences and collaborating within interdisciplinary stakeholder teams and thereby improve the representativeness and broader social support of results.

## Disclaimer

The International Energy Agency (IEA) is an intergovernmental organisation that works to shape a secure and sustainable future for all, through our focus on all fuels and all technologies, and our analysis and policy advice to governments and industry around the world.

The Technology Collaboration Programme (TCP) is a multilateral mechanism established by the IEA with a belief that the future of energy security and sustainability starts with global collaboration. The programme is made up of thousands of experts across government, academia and industry in 55 countries dedicated to advancing common research and the application of specific energy technologies.

Views of the IEA Hydrogen TCP and/or any of its Tasks are not those of the IEA.

IEA Hydrogen TCP-Task 42 focuses on supporting and accelerating the establishment of the technical, economic, and societal viability of underground hydrogen storage in porous reservoirs, salt caverns, and lined-rock caverns. TCP-Task 42 represents a global community of 54 organizations and more than 190 experts from industry, research, science and policy. The task commenced in January 2022 and is scheduled to continue until December 2024.

The contents of this Technology Monitor Report 2023 reflect only the views of the authors and do not necessarily reflect the opinion of any of the TCP-Task 42 organizations that are specifically acknowledged as contributing organization or mentioned as participant in TCP-Task 42.

## Acronyms and abbreviations

2D	Two-dimensional	PSA	Pressure Swing Adsorption
3D	Three-dimensional	R&D	Research and Development
4D	Four-dimensional spacetime: 3D space plus time	SEL	Societal Embeddedness Level
CAES	Compressed Air Energy Storage	SPE	Society of Petroleum Engineers
CAPEX	Capital Expenditure	SRL	Storage Readiness Level
CCS	Carbon Capture and Storage	SRMS	Storage Resource Management System
CCUS	Carbon Capture, Utilization and Storage (or Sequestration)	SSRM	Sulphur Species Reducing Microorganisms
CH <sub>4</sub>	Methane	SSSV	Subsurface Safety Valve
CO	Carbon monoxide	T	Temperature
CO <sub>2</sub>	Carbon dioxide	TCP	Technology Collaboration Programme
EU	European Union	TDV	True Depth Vertical
FEED	Front-End-Engineering-Design	TSA	Temperature Swing Adsorption
GIIP	Gas-initial-in-place	TRL	Technology Readiness Level
H <sub>2</sub>	Hydrogen	TSO	Transmission System Operator
H <sub>2</sub> S	Hydrogen sulphide	UGS	Underground (Natural) Gas Storage
HE	Hydrogen Embrittlement	UHS	Underground Hydrogen Storage
HIC	Hydrogen-Induced Cracking	UNFC	United Nations Framework Classification for Resources
HSE	Health, Safety and Environment	WTIR	Withdrawal To Injection capacity Ratio
IEA	International Energy Agency		
IFT	Interfacial Tension		
LCCS	Last Cemented Casing Shoe		
LHV	Lower Heating Value		
MIC	Microbiologically induced corrosion		
NASA	US National Aeronautics and Space Administration		
NGO	Non-Governmental Organization		
N <sub>2</sub>	Nitrogen		
NaCl	Sodium chloride		
NO <sub>x</sub>	Nitrogen oxides		
OCTG	Oil Country Tubular Goods		
OPEX	Operational expenditure		
P	Pressure		

## Overview of participating organizations in TCP-Task 42 (status March 2023)

### Europe

#### Netherlands

TNO - Netherlands Organisation  
for Applied Scientific Research  
Delft University of Technology  
Utrecht University  
EBN – Energie Beheer Nederland  
N.V. Nederlandse Gasunie  
Shell International Research  
Deltares  
Wageningen University & Research  
SodM - State Supervision of Mines  
Nobian

#### Italy

ENI  
University of Turin  
RSE S.p.A. - Ricerca sul Sistema  
Energetico

#### Spain

Trinity Energy Storage  
Fundación del Hidrógeno en Aragón  
CNH2 - Centro Nacional del  
Hidrógeno  
Repsol  
Enagas

#### Portugal

REN - Redes Energéticas Nacionais

#### France

Geostock  
University of Grenoble - Alps

#### Denmark

Gas Storage Denmark  
SaltPower

#### Germany

Helmholtz Centre Potsdam, GFZ  
Ruhr-University Bochum  
DBI Gas- und Umwelttechnik GmbH  
Storag-Etzel GmbH  
Technical University Bergakademie  
Freiberg

#### Austria

RAG Austria AG  
OMV Austria E&P GmbH

#### Norway

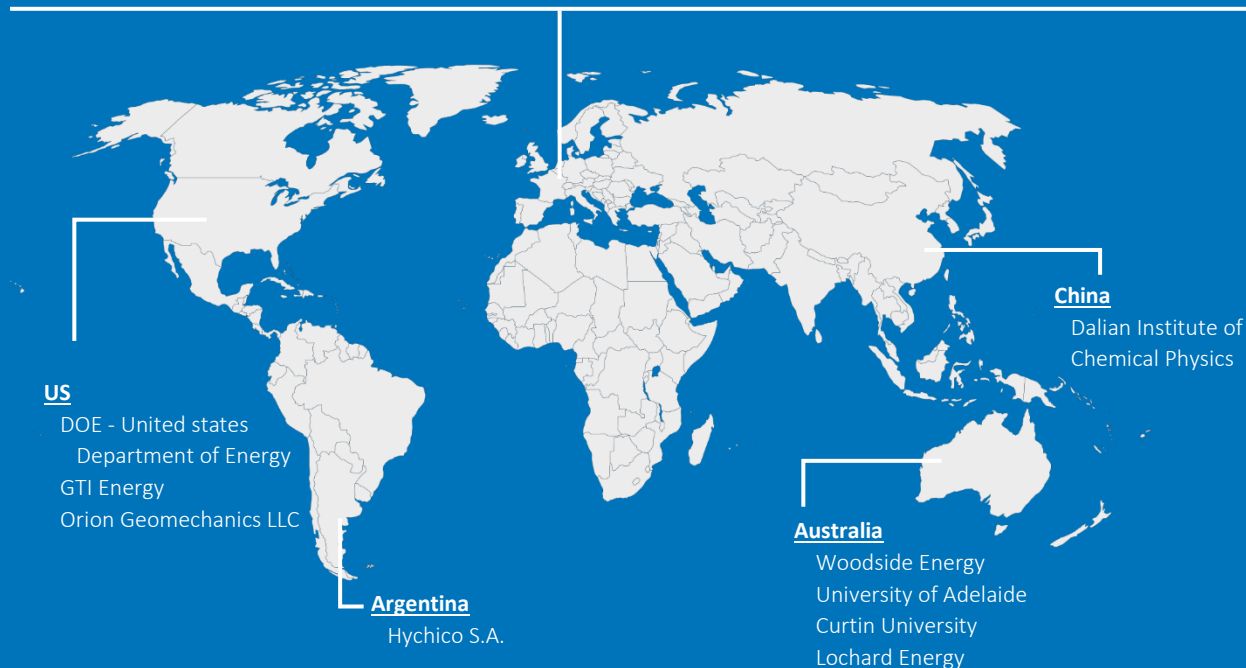
NORCE Norwegian Research  
Centre AS  
University of Bergen  
IFE – Institute for Energy Technology

#### United Kingdom

University of Edinburgh  
Edinburgh Napier  
University  
Centrica Storage Ltd  
BP International Ltd  
RPS Energy  
University of Birmingham  
BGS British Geological Survey  
Atkins Ltd  
Applied Seismology  
Consulting  
Heriot Watt University  
Halliburton

#### European Union

Clean Hydrogen  
Joint Undertaking



World map source: [simplemaps.com](https://www.simplemaps.com)

# CHAPTER 1

## General Introduction



Rationale for underground hydrogen storage

State of play and technical readiness

Introduction to Hydrogen TCP-Task 42 scope and objectives

Report scope and structure



# 1 General introduction

## 1.1 Rationale for underground hydrogen storage

The potential introduction of hydrogen as an energy carrier has recently gained attention from policymakers and industry. Global and regional energy scenarios and transition roadmaps foresee a prominent role for low-carbon hydrogen in the future energy system, given the urgent need to replace fossil energy by fluctuating renewable energy [1]. Projections of hydrogen production and end-uses predict a six- to seven-fold increase between now and 2050 [2, 3].

Hydrogen is considered as a crucial energy carrier enabling variable renewable energy integration, which provides crucial flexibility to the electricity grid and helps to decarbonize other sectors characterised by high energy demand such as industry, heavy transport and the built environment. The steep growth of intermittent sources of energy production (e.g., wind and solar) and continuing seasonal energy consumption patterns (e.g., residential heating) will require large-scale balancing capacities at hourly, daily and inter-seasonal timescales as well as solutions for energy security and provision of strategic reserves. For that purpose, underground hydrogen storage (UHS) [4, 5] has been identified as an essential core technology for which hardly any alternatives exist in terms of capacity and performance.

In the present situation, the majority of energy is still being stored in underground natural gas (UGS) sites. Since the first UGS became operational in a depleted gas field in Ontario (Canada) in 1915, UGS has been deployed in depleted gas fields, aquifers, salt caverns and lined rock caverns [6]. Currently, some 662 UGS facilities are in operation world-wide, of which 72% are deployed in depleted hydrocarbon reservoirs, 15% in salt caverns and 11% deep aquifers [7]. In 2019, the total global operational work volume at UGS facilities was approximately 483 bcm (approximately 5,200 TWh) [8]. This volume resembles ca. 12% of the total global annual natural gas demand (3,986 bcm [9]) in that same year. In Europe the total operational working gas volume for UGS (1,572 TWh [10]) is approximately 29% of the total annual natural gas demand (5,411 TWh [11]).

Projections for UHS demand are still highly uncertain [12]. IRENA reports an expected total global working gas volume of 670 bcm in 2050 [13], whereas Europe Statista forecasts a volume of approximately 150 bcm (450 TWh) [14]. When assuming a 10 – 12% hydrogen storage – to – hydrogen demand ratio together with a total global hydrogen demand of approximately 17,000 TWh in 2050 [15], the total required UHS working volume would be in the same order of magnitude (i.e., 580 – 600 bcm) and thus similar or even greater than the total working volume of UGS today.

## 1.2 State of play

### 1.2.1 Past experiences

Although UHS has many technical commonalities with UGS (similar reservoirs and general operational principles), it is still in a very early stage of development. Table B-2 and B-3 in Appendix B summarize past, present and planned UHS experiences and projects. There is several decades of experience with the commercial operation of underground storage of mixtures composed of ca. 50% hydrogen and various other gases such as methane, carbon dioxide and nitrogen (so-called town gas) in porous reservoirs, see [16, 17, 18, 19] and Table B-1 in Appendix B. There are three sites in the United States and one site in the United Kingdom where at least 95% pure hydrogen is being commercially stored in salt caverns at an industrial scale (Figure 1-1).

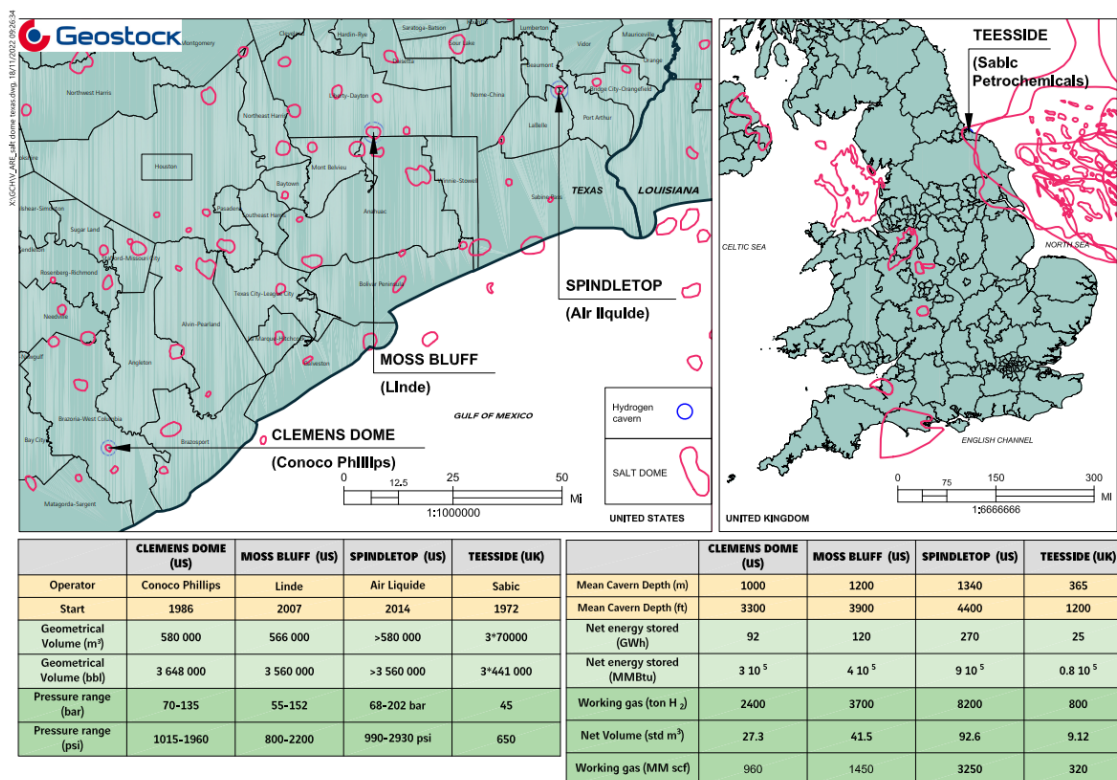


Figure 1-1: First pure hydrogen storage facilities and their main characteristics [20].

Furthermore, there are two established pilot facilities in Austria and Argentina that have conducted injection and withdrawal tests with mixtures of 20% hydrogen and 80% natural gas in depleted gas fields. None of these sites is currently commercially deployed as flexibility service in the energy system.

A first pilot facility for pure hydrogen storage in a small, depleted gas reservoir is expected to be deployed in 2023 in Austria. Several other projects expect to test and demonstrate storage of pure and blended hydrogen in salt caverns, lined rock caverns or depleted gas fields (Table B-2, Appendix B). All these projects are still in a prefeasibility or design stage.

The deployment of UHS at larger scale, with the objective of contributing to net-zero energy systems, however, requires overcoming many technical, economic and social barriers. Storage in both porous rock and salt caverns is associated with questions regarding potential geochemical and microbial reactions between hydrogen, the host rock and fluids that may result in a conversion and contamination of stored hydrogen or affect the reservoir performance in addition to potential leakage issues.

### 1.2.2 Suitable geological formations for underground hydrogen storage

Figure 1-2 shows a schematic overview of subsurface options that are currently considered for underground hydrogen storage. Depending on the type of reservoir and purity of hydrogen, the current technical development is either at a conceptual (pre-validation) level or in the stage of preparing large prototypes and precommercial pilots. There is a need for timely demonstration of UHS at the expected scale of future commercial operation. The typical long lead times for underground storage projects and the potentially rapid development of storage demand after 2030 should be taken into account.

The different properties and behaviour of hydrogen pose a range of fundamental and practical challenges, which need to be resolved before the technology becomes mature enough for commercial

operation. This concerns among others i) the high reactivity of hydrogen, ii) very low density at standard conditions and associated increased buoyancy in the gas column, iii) relatively low viscosity compared to methane and carbon-dioxide, iv) high diffusivity and thermal conductivity, and v) low solubility in water. While isolated laboratory studies are ongoing, UHS concepts need to be tested and validated in a real subsurface environment. The planning, upscaling and integration of UHS in the future energy system depends on a comprehensive geological screening of suitable reservoirs, evaluation of viable and safe subsurface and operational conditions, assessment of environmental and societal impacts, determination of surface restrictions and spatial integration options, and analysis of viable business models and concepts. These insights form the basis for establishing a robust regulatory framework and best practices for responsible and societally accepted development of UHS.

**Salt caverns:** Hollow cylindrical voids in a rock salt formation in the subsurface created by salt solution mining. These voids are irregular in morphology but typically these are on the scales of a diameter of several tens of meters and heights of several hundreds of meters. The bottom of caverns is located at depths of up to two kilometres. Rock salt is a proven seal for natural gas, hydrogen and various other types of gases such as nitrogen and helium.

**Depleted gas fields:** Storage capacity defined by the pore space in a (once) gas-bearing rock formation. This typically concerns sandstone carbonate intervals. The storage volume results from prior extraction of hydrocarbons. Gas fields are sealed by impermeable cap rocks such as mudstones and rock salt, which are proven to be a capable seal for natural gas. The seal integrity for hydrogen gas is being tested.

**Aquifers:** Storage capacity defined by the porous, water bearing rock formations. The presence of a secure and gas-tight seal must generally be proven by geological investigations, exploration drilling and injection tests.

**Lined (hard) rock caverns:** Man-made tunnels and caverns built in low permeable rock formations. The secure containment for gases is generally achieved by lining the cavern walls with a gas-tight material.

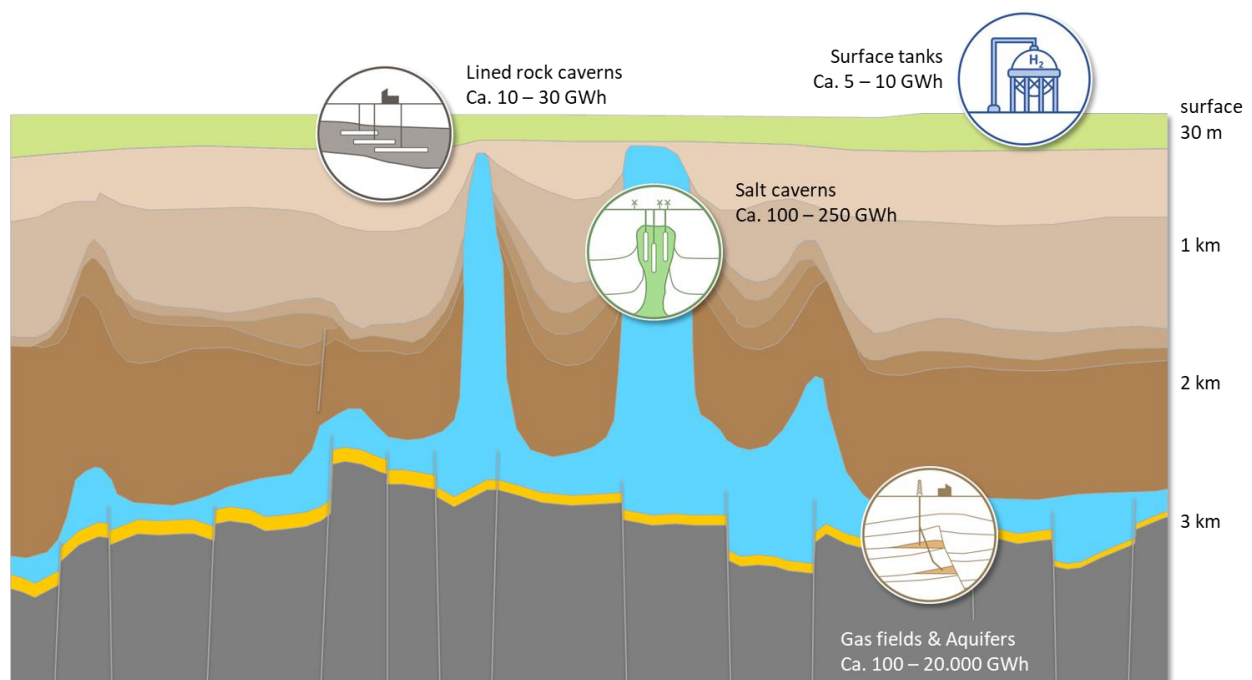


Figure 1-2: A schematic overview of different technologies considered for UHS, including typical ranges for storage capacities.

### 1.2.3 Technology Readiness Level

Technology readiness assessments have traditionally been applied to engineered (man-made) technologies and systems and primarily to “active” components or systems [21]. Because an underground storage system is comprised of both engineered barriers and natural or geologic barriers, the technology maturation process and any associated Technology Readiness Assessment must be expanded beyond what is applicable to a strictly engineered facility. It should be noted that each geological reservoir has its own unique technical challenges that need to be locally tested and demonstrated. Unlike engineered and man-made technology, the geological concepts may not simply be reproduced and commercialized at large scale without extensive site-specific assessments.

The Technology Readiness Level (TRL) approach provides a structured sequence of activities and milestones to assess and progress the degree of maturity of a new technology or capability [22]. Developed originally by NASA in the mid-1970s, it has been adopted by others including the US Department of Defence [23], aerospace companies in the US, Japan, and Europe, spent nuclear fuel [21], CO<sub>2</sub> sequestration in salt caverns [24], and the Horizon 2020 program funded by the EU.

The International Energy Agency (IEA) defines 11 levels of technical readiness [25]. This framework incorporates the typical TRL levels ranging from “1. basic principles reported” up to “9. full system proven in an operational environment” [22], and which are extended by two additional levels to describe the upscaling of the technology as follows:

- TRL 10: Technology is commercial and competitive, yet requires further integration efforts to scale up. For UHS this means that further integration in the energy system will commence.
- TRL 11: Technology has achieved stable and predictable growth. This level corresponds to a “mature” UHS facility that meets energy policy objectives such as resilience.

Progressing a technology or capability through TRL may reduce the technical risk profile of its implementation. However, capital expenditures generally increase with increasing TRL, leading to an increase in investment risk. A technology readiness assessment provides a snapshot in time of the level of maturity of a given technology or capability. Levels can overlap and run concurrently, with feedback loops of continuous improvement and innovations. Readiness levels can accelerate or slow down – or even stop – depending on technical or cost factors, and a project can be at different readiness levels in different markets.

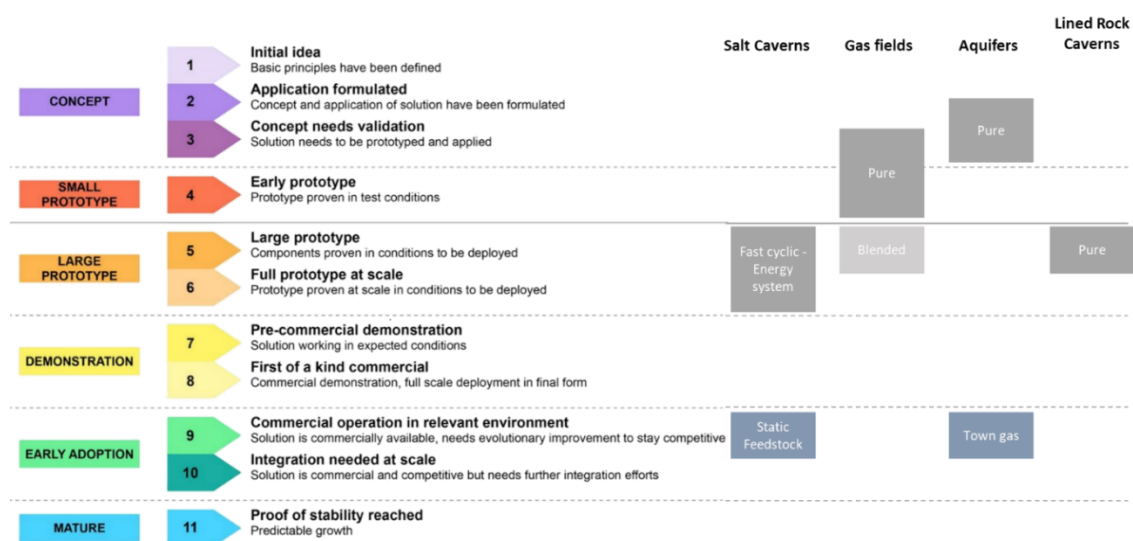


Figure 1-3: Overview of Technical Readiness Levels for different UHS technologies according to the IEA TRL framework [25].

Table 1-1: Estimation and clarification of current Technical Readiness Levels according to IEA [25].

Hydrogen Storage in salt caverns	TRL 5 – 6 for pure hydrogen in fast-cyclic energy system setting	Storage of pure hydrogen at slow-cyclic operations is operationally and commercially demonstrated at sites in the UK and the US. These include salt cavern storage of hydrogen with small volumes at three shallow salt caverns in Teesside (United Kingdom) and deeper, large-volume salt caverns at three locations in the United States (Spindletop, Clemens Dome and Moss Bluff, all storing ca. 95% hydrogen). The application for fast-cyclic energy system applications is currently being tested in pilot projects (e.g., HyStock, the Netherlands [26]) and various other pilots are underway (among others Hypster, France [27], H <sub>2</sub> Cast [28], Krummhörn [29], both Germany). Some pilots investigate the possibility to reuse caverns that have been used before for storage of natural gas and crude oil. Drilling and cavern construction techniques are technically mature. The main aspects under investigation are the integrity of the cavern and wells under fast-cyclic operation as well as the risks of conversion, losses and contamination of stored hydrogen due to microbial processes.
	TRL 9 for static or low-cyclic feedstock applications based on pure hydrogen	
Hydrogen storage in depleted gas fields	TRL 3 – 4 for pure hydrogen	Two successful pilots have been conducted with hydrogen blends (10 – 20%) in depleted gas fields (Sun Storage, Austria [30] and Hychico, Argentina [31]). Pure hydrogen storage in a depleted gas field has not been tested but a field-scale pilot is now underway (Sun Storage 2030, Austria [32]). At various other locations the repurposing of depleted or UGS-deployed gas fields for hydrogen storage is being considered. Some of the components in the gas storage system (facilities, wells, pipes and reservoir) need to be tested for use with pure hydrogen. The operations and effectiveness of storage will likely be affected by the different characteristics of hydrogen (geochemical and microbial conversion, thermodynamic behaviour, flow, containment and mixing of hydrogen with other gases). Depleted gas fields are among the most appropriate options to store very large volumes of natural gas. Demonstrating their feasibility for hydrogen storage is of great interest nowadays [33, 34].
	TRL 5 for hydrogen natural gas blends (10 – 20%), taking into account the quality specification for application in the energy system	
Hydrogen storage in saline aquifers	TRL 2 – 3 for pure hydrogen	Storage of pure hydrogen in aquifers is still conceptual and needs to be prototyped. The important difference with depleted gas fields is that the risk of contamination with other gases is not yet understood for aquifers. Much less is known about the standard set of reservoir properties due to the lack of exploration data and production experiences. Storage of town gas, containing up to 50-60% hydrogen, was commercially deployed for a long time at several sites [35]. These projects have, however, shown that hydrogen losses can be expected due to microbial processes and in conclusion there is a need for further investigation and testing of these aspects in porous reservoirs in general.
	TRL 9 for town gas (blends of hydrogen with methane, carbon dioxide, nitrogen, etc.)	
Hydrogen storage in lined (hard) rock caverns	TRL 5 for pure hydrogen based on a local project	An operational pilot for storage of pure hydrogen in a lined rock cavern has recently been established in Sweden (Hybrit project, [36]). The cavern is relatively small and comprises 100 m <sup>3</sup> geometric volume. The intention is to expand the cavern to a larger (100,000 m <sup>3</sup> ) volume for commercial operation. Lined rock caverns can be fully engineered using tunnel engineering technologies and the lining of cavern walls with hydrogen resistant materials which are currently investigated. This would support reproduction in similar projects at other geologically suitable locations.



Underground storages represent complex systems, each of which is comprised of several main technologies (e.g., well engineering, reservoir characterization, development and engineering, flow assurance, gas processing) [24]. Each main technology can be further subdivided into subcomponents and technologies such as drilling, well casing/tubing and pumps. Each of these components may have their own TRL that should finally be integrated into a system-wide TRL.

As is mentioned in Section 1.1, the subsurface reservoirs shown in Figure 1-2 are already fully matured and deployed at scale for underground storage of natural gas and, in the case of salt caverns, for liquid hydrocarbons. The application of the concept for UHS is at a significantly lower technical maturity level, which is largely due to the specific characteristics of hydrogen and resulting expected impacts on operations and safety. At present there is no existing market for the integration of UHS in an energy system context (e.g., providing flexibility, balancing and supply security services) and in most countries there still is a need to raise the societal embeddedness (e.g., establishing frameworks for environmental impact assessments, regulations and policies, stakeholder involvement and public engagement).

Figure 1-3 and Table 1-1 provide an expert-judged estimation and clarification of TRLs for various types of UHS systems, following the IEA classification framework [25]. A comprehensive overview of past experiences and future plans for demonstration and development is provided in Appendix B.

### 1.3 Hydrogen Technology Collaboration Programme – TCP-Task 42

In January 2022 the International Energy Agency's Hydrogen Technology Collaboration Programme (TCP) implemented TCP-Task 42 which focuses on supporting and accelerating the establishment of the technical, economic and societal viability of underground hydrogen storage in porous reservoirs, salt caverns and lined-rock caverns. The main objectives of this task are to:

- Provide a comprehensive assessment of the general technical and economic feasibility of large-scale UHS development.
- Deliver insights and information regarding the potential and limitations of UHS development in the involved countries based on publicly available results from technical and economic feasibility studies.
- Assess advantages and disadvantages of UHS in different settings such as onshore and offshore, and evaluate what may be needed in terms of legacy infrastructure or remediation assessments.
- Investigate subsurface conditions for safe and technically viable hydrogen storage in different types of reservoirs by generating, evaluating and compiling relevant results from laboratory experiments, field measurements and numerical modelling work and other geological studies.
- Expand the understanding of residual risks associated with UHS deployment, and thereby support informed decisions on responsible commercialization and upscaling.
- Present policy makers and other stakeholders with information and recommendations which support informed decisions on responsible and economic UHS development in porous reservoirs, salt caverns and other man-made caverns.
- Seek opportunities for synergy and complementary activities that prevent unnecessary duplication in research, save time and money and support acceleration of UHS.



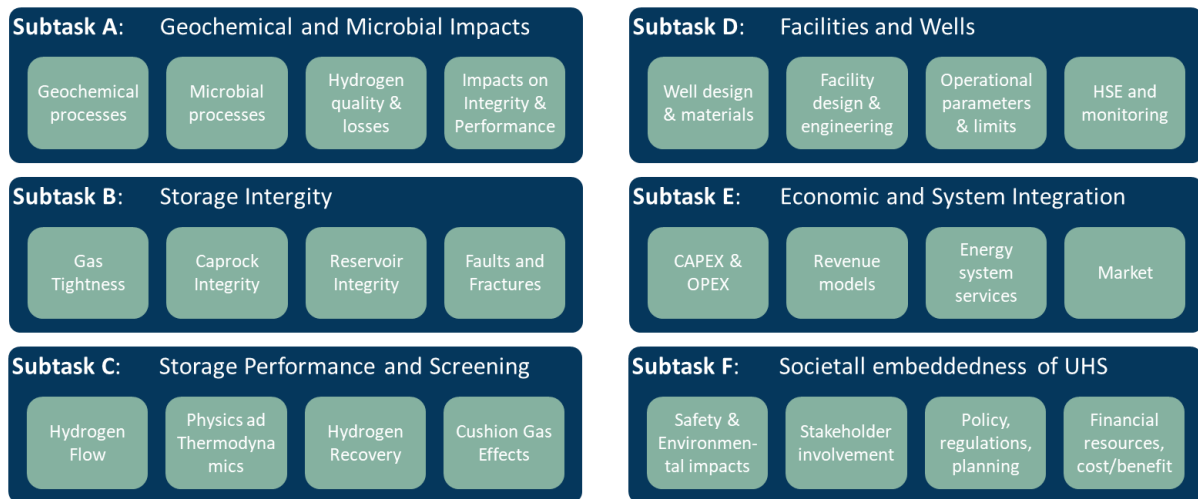


Figure 1-4: Overview of the TCP-Task 42 R&D pillars and topics.

TCP-Task 42 is subdivided into six thematic subtasks (Figure 1-4) that are underpinning the technical, economic, environmental and social viability of UHS projects. Three subtasks (A, B and C) are directly related to the geological characteristics of the subsurface storage complex and the geological processes and impacts that take place in the presence of injected and stored hydrogen. Although there are general learnings that can be obtained for subsurface characteristics and processes, the key challenge will always be to assess the subsurface suitability and impacts in the specific local setting where development takes place in order to minimize uncertainties. The other three subtasks address engineering, economics and social aspects. In practice there are interdependencies between subtask aspects (e.g., economics being determined by geological characteristics and engineering solutions).

Figure 1-5 provides a holistic overview of different interlinked and interacting domains that are relevant for UHS development. Each domain can be linked to specific aspects addressed in the individual subtasks. Table 1-2 provides an overview and description of typical challenges and questions for each domain that need to be resolved to mature the level of technical, economic and societal readiness for a safe and responsible development and commercialization of UHS.

## 1.4 Report scope and structure

This report aims to provide a comprehensive overview of the current state-of-the-art and key developments that have emerged from latest research works, literature sources and experiences within the TCP-Task 42 community and many UHS science events. The report focuses on storage of pure hydrogen gas in underground formations. Many aspects of pure hydrogen storage are also relevant for underground storage of hydrogen/natural gas blends and are thus considered as part of the scope. Underground storage of natural gas (UGS) is not investigated in this report, yet the many experiences and knowledge on geological, technical and operational aspects of this mature technology are also relevant for UHS and are therefore regularly mentioned throughout the report.

The key questions being addressed strongly focus on what is needed to enable and accelerate UHS demonstration and implementation, i.e.:

- What is currently known about the various aspects of UHS and how does that knowledge impact the prospects of development and operation?
- What key actions are required to improve the techno-economic readiness of UHS as well as the social license to operate, and how can UHS development and demonstration benefit from available fundamental knowledge and vice versa?

Table 1-2: Overview of typical challenges and key questions for each domain described in Figure 1-5.

<b>Geological Domain</b>	<p>Which geological formations are suitable for storing and recovering hydrogen?</p> <p>How does hydrogen flow in the subsurface under different geological conditions?</p> <p>How is hydrogen impacted under different geological conditions, including losses and reaction by-products</p> <p>How do hydrogen and reaction products impact the subsurface?</p> <p>How do any of the above impacts propagate to the technical, system and social domain?</p>
<b>Technical Domain</b>	<p>What technical components and designs are needed for a safe and effective injection and recovery of hydrogen?</p> <p>To what extent can existing infrastructure be repurposed and will legacy wells impact UHS</p> <p>How do hydrogen and its reaction products impact wells, facilities and materials?</p> <p>What is the safe operating window for injection and recovery of hydrogen?</p> <p>How do geology and storage demand influence the facility design, location and costs?</p>
<b>Energy System Domain</b>	<p>How much storage capacity is required, where is it required, and when?</p> <p>What are the hydrogen grid requirements with regards to hydrogen injection and recovery including rates, cyclicity, availability and quality?</p> <p>What are the business models for underground hydrogen storage?</p> <p>What are the viable alternatives?</p>
<b>Social Domain</b>	<p>What are the environmental impacts of UHS?</p> <p>What are the social benefits and costs?</p> <p>Which stakeholders are involved and what are their roles and responsibilities?</p> <p>What policies, regulations, engagements and financial resources are needed for a timely and socially accepted development of UHS and to secure clean and affordable energy and feedstock resources?</p>

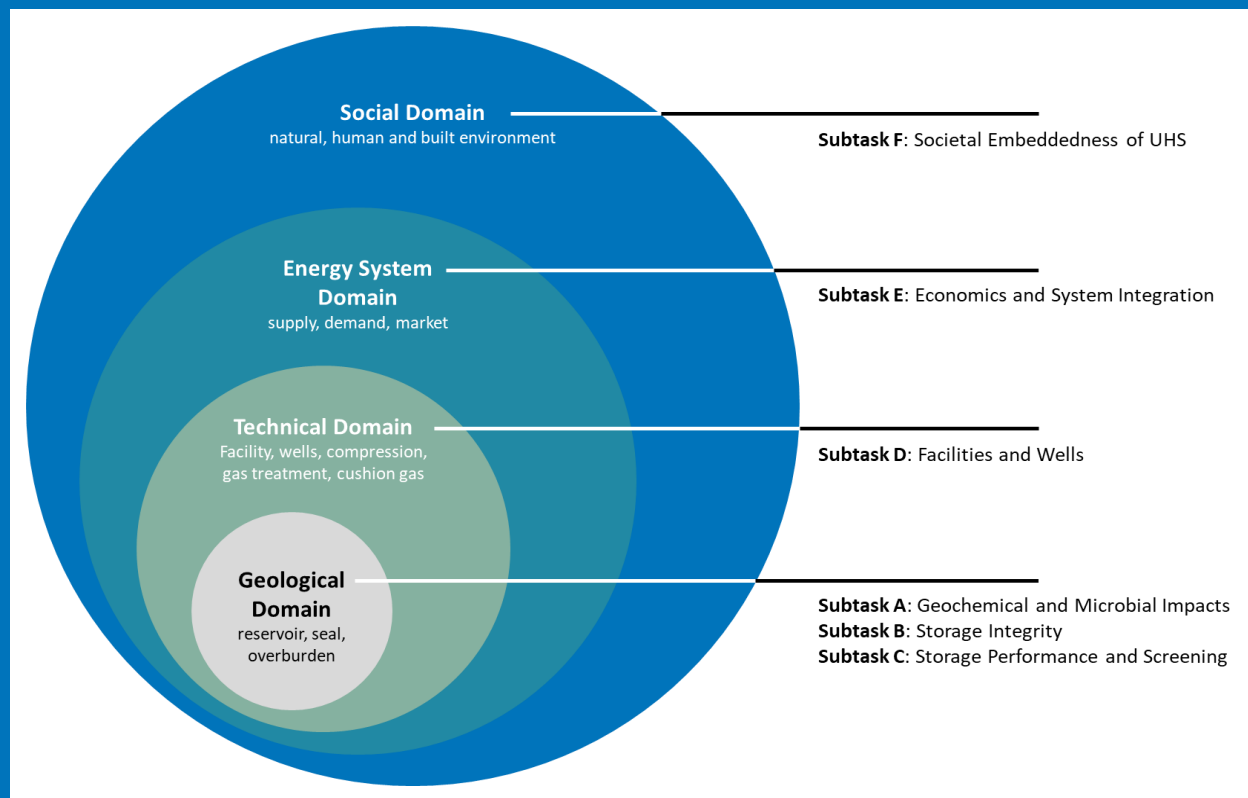


Figure 1-5: Schematic overview of domains that are important for reaching a mature and responsible development stage of UHS.

The report addresses these questions along the lines of the main subtasks presented in Figure 1-4, emphasizing relevant interdependencies where present, and differentiating between the different reservoir types and technologies considered (e.g., salt caverns and porous rock formations).

**Chapter 9 (Synthesis and outlook)** presents a synthesis of main findings and recommended actions towards implementation of UHS for each storage technology. More specific findings and actions for each thematic subtask are presented in the final sections of Chapters 2 – 8. For those interested, these chapters also provide a more detailed and comprehensive technical summary.

A brief overview of the scope of each chapter is provided below:

**Chapter 2 (Geochemical and microbial processes)** summarizes what is currently known about the different geochemical and microbial processes and what reservoir conditions and characteristics are responsible for triggering these. It includes recommendations towards improving the understanding of these processes and how to prevent or mitigate negative impacts.

**Chapter 3 (Storage integrity)** addresses the capability of reservoirs and seals to safely contain injected hydrogen. It evaluates the state of art on how storage integrity is affected by cyclic injection and withdrawal of hydrogen and by the various geochemical and microbial processes impacting the reservoir and cap rock.

**Chapter 4 (Storage performance)** zooms in on the factors that define the performance of suitable hydrogen storage reservoirs including hydrogen flow, recovery and cushion gas effects. Examples are given on how to better predict the flow behaviour of hydrogen and optimize performance while minimizing risks.

**Chapter 5 (Geological characterization, screening and ranking)** summarizes the learnings from various national and regional geological screening and characterization studies, taking into account the selection criteria based on experiences from chapters 2 – 4. This includes recommendations to increase the reliability of reservoir assessments for UHS deployment and to support the screening, storage capacity estimation, selection and planning of suitable UHS candidates.

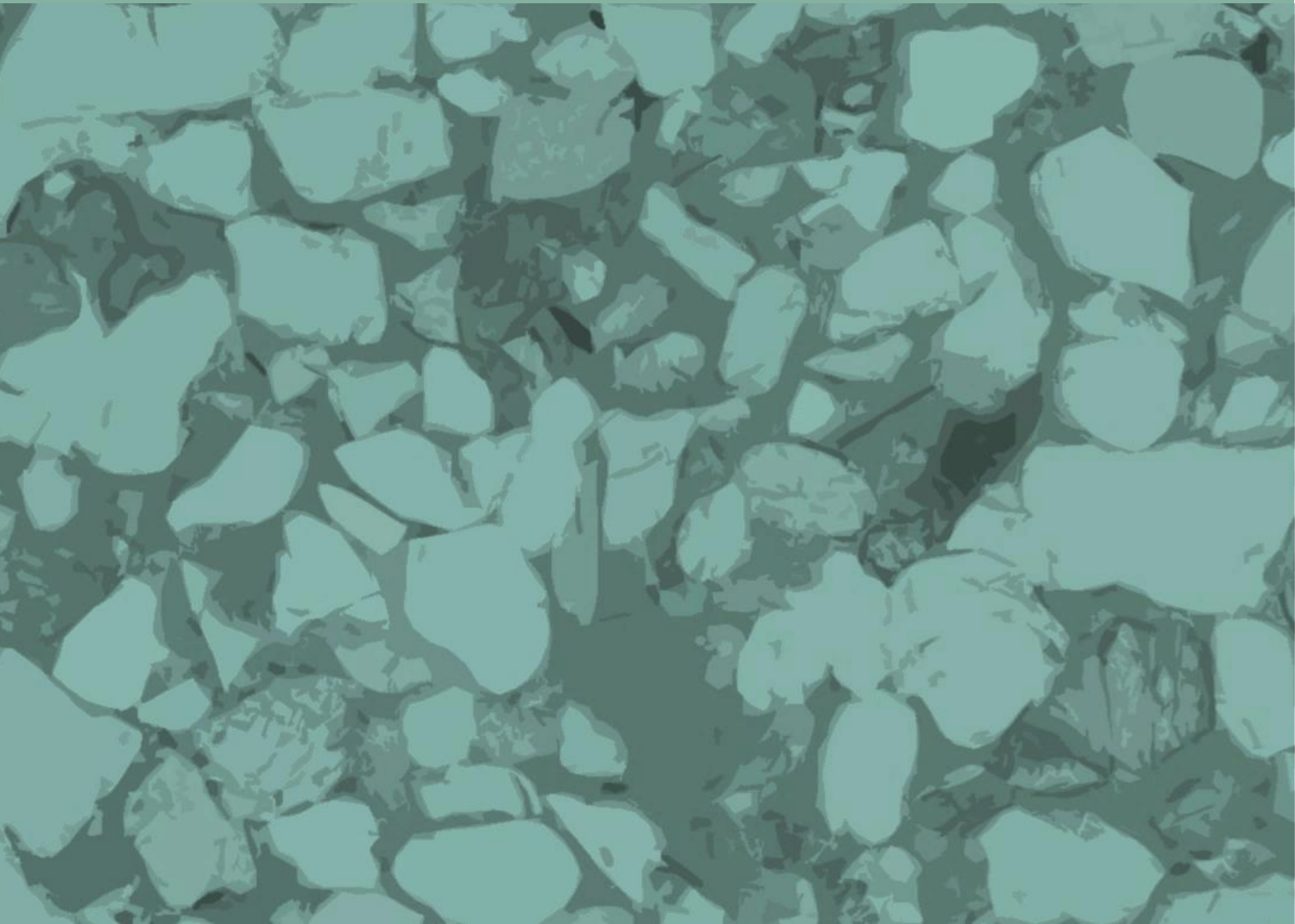
**Chapter 6 (Facilities and wells)** provides an overview of typical facility and well designs and technical components (including materials and specifications) that are required to operate an UHS site. It addresses typical operational parameters and safety limits, the impacts that can be expected from using hydrogen as storage gas and what safety and monitoring concepts are available.

**Chapter 7 (Economics and cost estimations)** evaluates the cost breakdown (CAPEX and OPEX) for developing new UHS sites and addresses issues such as costs controlling factors, cost uncertainties and options to reduce these uncertainties.

**Chapter 8 (Societal embeddedness of underground hydrogen storage)** evaluates a generic framework to determine and increase the level societal embeddedness of UHS. The chapter presents a methodology and approach to mature the social aspects related to environmental impacts, stakeholder involvement, UHS policy and regulation, market and financial resources.

# CHAPTER 2

## Geochemical and Microbial Processes



Geochemical processes

Microbial processes

Impacts on development and operations

## 2 Geochemical and microbial processes

### 2.1 General introduction

This chapter evaluates geochemical reactions and microbial processes associated with hydrogen storage in porous rock formations, solution-mined salt caverns and engineered rock caverns. Of particular concern are (i) the promotion of abiotic geochemical reactions between reservoir rocks, formation fluids and stored hydrogen, and (ii) the fact that hydrogen is an electron donor for a variety of microbial processes. Figure 2-1 illustrates a number of key components within the subsurface system that play their part in driving the geochemical and microbiological reactions including the well casing, well cement (e.g., Portland cement mixes), seals and caprocks (shale/salt), porous reservoir rocks (sandstone/limestone), overlying and underling formations (all rock types), formation fluids (brine, hydrocarbons), dissolved or free gas ( $\text{CH}_4$ ,  $\text{CO}_2$ , etc.) and of course the stored hydrogen.

Abiotic and biotic reactions may be detrimental to underground hydrogen storage through hydrogen losses, compositional changes of the stored hydrogen, mineral precipitation and dissolution, biomass/biofilm formation, as well as well cement and casing degradation, which may impact reservoir integrity and recovery efficiencies. Whenever relevant, these processes and effects are distinguished for salt caverns, porous reservoirs and rock caverns. For geochemistry the reporting is based on a mineral-oriented perspective, which then allows for applications for both caverns and porous environments. In the microbiology section some information is presented in the specific context of either porous reservoir or cavern storage. The chapter concludes with a summary of key challenges and impacts, the current available knowledge and capabilities to address these challenges, and recommendations to resolve existing information and knowledge gaps and thereby enable a responsible and safe implementation of UHS from geochemical and microbiological point of view.

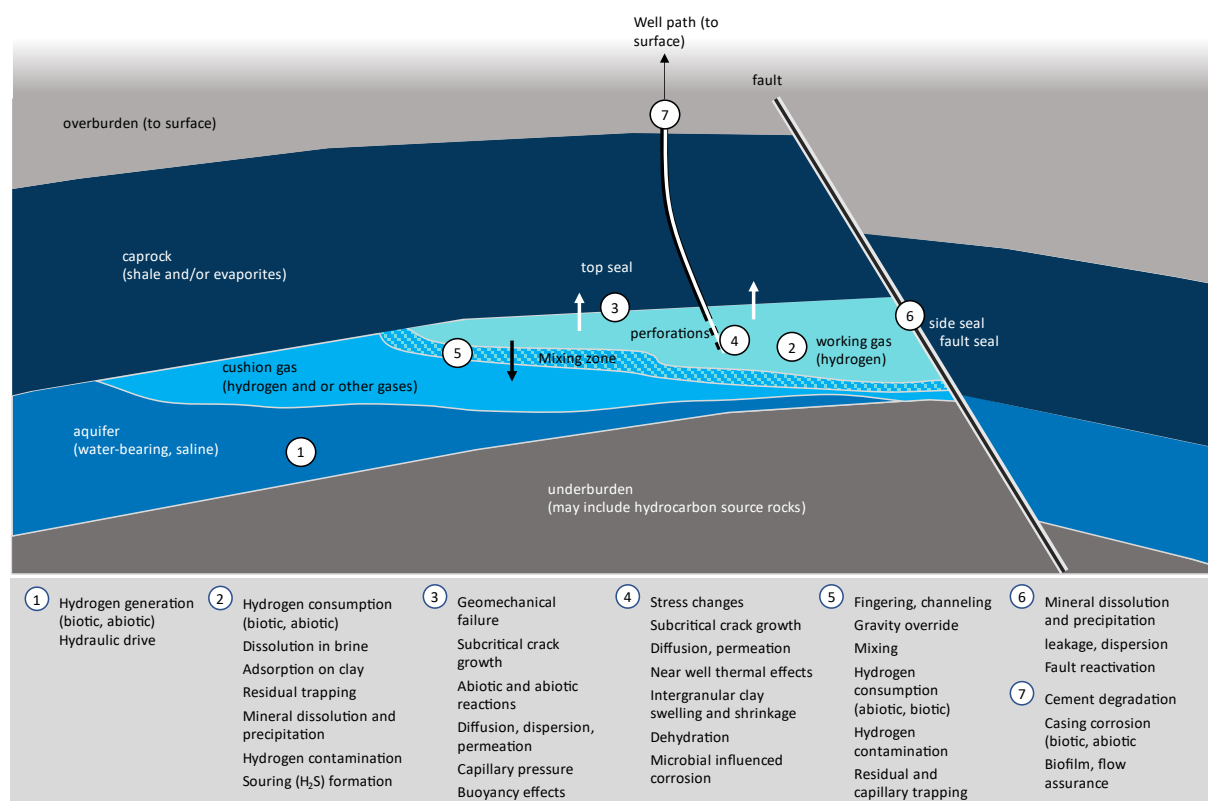


Figure 2-1: Geochemical and microbial processes that impact underground hydrogen storage, modified from [37].

## 2.2 Geochemical processes

### 2.2.1 General context

Mineral reactions can be induced by changing reservoir pressure and temperature during injection, storage and production of hydrogen as well as the presence of hydrogen as free gas coupled with its partitioning into the formation fluids. Hydrogen dissolved in the aqueous phase can react with minerals that are sensitive to redox reactions. This interaction can lead to mineral dissolution/precipitation, mineral mobilization, and thus changes in the flow and mechanical properties of the storage rocks, hydrogen consumption, gas composition changes and H<sub>2</sub>S, CO<sub>2</sub> or CH<sub>4</sub> generation. Furthermore, in the salt cavern environment, the stored hydrogen can dissolve partly into the brine which is then in contact with the mineral-rich sump at the bottom of the cavern. The sump can supply minerals to the brine layer which is then in presence of the dissolved hydrogen can react, with the bacterial influence. This can lead to impurities in the hydrogen phase, specially the unwanted H<sub>2</sub>S [38]. All of these processes, within porous and cavern reservoirs, influence the operation, capacity, and long-term safety and stability of the storage site.

Within the context of underground hydrogen storage in porous media, salt caverns and rock caverns, most of the potential abiotic reactions, e.g., the reduction of sulphates and carbonates, remain kinetically limited [39, 40]. The reductive dissolution of iron oxides and reduction of pyrite, leading to the formation of hydrogen sulphide, are reactions that are potentially kinetically fast enough to impact underground hydrogen storage [41].

The main factor that prevents the occurrence of extensive hydrogen associated reactions is the strong binding energy of the HH bond, which requires the overstepping of a 436 kJ/mol activation energy [42]. Therefore, hydrogen reactions require surface catalysis, or microbial mediation to occur. In addition, the non-polar nature of hydrogen limits its solubility in formation fluids, which is influenced by pressure, temperature and salinity. As such, hydrogen gas in reservoir systems has an extremely low solubility which typically only reaches 0.14 M/l at 65 °C and 20 MPa, limiting the reactivity of hydrogen. Furthermore, rates of geochemical reactions are temperature dependent, and therefore lower temperatures present a lower risk for geochemical reactions, while reservoirs at temperatures above 80 °C are more likely to be affected. Consequently, hydrogen induced abiotic redox reactions are rarely observed in low to medium temperature (30 – 150 °C), pressure (50 – 300 bar) and salinity settings on timescales relative to seasonal hydrogen storage (0 – 30 years).

The role of mineral surfaces as a potential catalyst should not be neglected. These surface reactions may influence gas compositions in the storage environment, induce hydrogen losses, and may also contribute to corrosion of engineering facilities.

Table 2-1 lists the minerals that have been identified as susceptible to hydrogen, including reactions that are unlikely to occur at hydrogen storage conditions.

### 2.2.2 Experience of geochemical processes from past and ongoing projects and studies

#### Research projects and publications

The work undertaken so far to establish the risks associated with geochemical reactivity during underground hydrogen storage has primarily focused on laboratory scale investigations. Table B-2 in Appendix B presents ongoing or recent research projects among which several investigating geochemical and microbial reactivity during hydrogen storage. Some experimental investigations into geochemical reactivity during hydrogen storage at realistic reservoir conditions suggests that sulphide and ferric iron associated minerals can be considered to be potentially reactive in the presence of hydrogen, but that the risk of geochemical reactivity in storage reservoirs depends on the temperature of the reservoir. At low temperatures (T=60 °C) the risk for geochemical reactions appears low, while



the impact at higher temperatures, (T around 80 °C or higher), warrants further investigation. However, it is important to note that of the fifteen relevant published studies, only five studies have been undertaken at temperatures and pressures representative of underground storage and only two present detailed geochemical analysis of both rock and fluid chemistry, the others are visual or petrophysical studies.

Table 2-1: Minerals susceptible to hydrogen.

Carbonate minerals. $\text{CO}_3^{2-}$ can be reduced to $\text{CH}_4$ with the by-products of water and $\text{OH}^-$ .	
Calcite:	$\text{CaCO}_3 + 4\text{H}_2 \rightarrow \text{Ca}^{2+} + \text{CH}_4 + 2\text{OH}^- + \text{H}_2\text{O}$
Dolomite:	$\text{CaMg}(\text{CO}_3)_2 + 8\text{H}_2 \rightarrow \text{Ca}^{2+} + \text{Mg}^{2+} + 2\text{CH}_4 + 4\text{OH}^- + 2\text{H}_2\text{O}$
Magnesite:	$\text{MgCO}_3 + 4\text{H}_2 \rightarrow \text{Mg}^{2+} + \text{CH}_4 + 2\text{OH}^- + \text{H}_2\text{O}$
Siderite:	$\text{FeCO}_3 + 4\text{H}_2 \rightarrow \text{Fe}^{2+} + \text{CH}_4 + 2\text{OH}^- + \text{H}_2\text{O}$ (For Siderite ( $\text{FeCO}_3$ ) and Fe-dolomite dissolution, the released iron can scavenge released $\text{H}_2\text{S}$ , forming Pyrrhotite ( $\text{FeS}$ ).
Dawsonite:	$\text{NaAlCO}_3(\text{OH})_2 + 4\text{H}_2 \rightarrow \text{Al}^{3+} + \text{Na}^+ + \text{CH}_4 + 4\text{OH}^- + \text{H}_2\text{O}$
Sulphate minerals. The sulphate ion $\text{SO}_4^{2-}$ can be reduced by stored hydrogen and generate $\text{H}_2\text{S}$ (in gas/aqueous phase or further dissociate into $\text{HS}^-$ ).	
Anhydrite:	$\text{CaSO}_4 + 4\text{H}_2 \rightarrow \text{Ca}^{2+} + \text{H}_2\text{S} + 2\text{OH}^- + 2\text{H}_2\text{O}$
Gypsum:	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O} + 4\text{H}_2 \rightarrow \text{Ca}^{2+} + \text{H}_2\text{S} + 2\text{OH}^- + 4\text{H}_2\text{O}$
Anglesite:	$\text{PbSO}_4 + 4\text{H}_2 \rightarrow \text{Pb}^{2+} + \text{H}_2\text{S} + 2\text{OH}^- + 2\text{H}_2\text{O}$
Barite:	$\text{BaSO}_4 + 4\text{H}_2 \rightarrow \text{Ba}^{2+} + \text{H}_2\text{S} + 2\text{OH}^- + 2\text{H}_2\text{O}$
Celestite:	$\text{SrSO}_4 + 4\text{H}_2 \rightarrow \text{Sr}^{2+} + \text{H}_2\text{S} + 2\text{OH}^- + 2\text{H}_2\text{O}$
Sulphide minerals, of which pyrite ( $\text{FeS}_2$ ) is one of the most common. In the presence of hydrogen, pyrite can be partially transformed to pyrrhotite, mackinawite or troilite ( $\text{FeS}$ ) and associate into $\text{H}^+$ to $\text{HS}$ and $\text{H}_2\text{S}$ .	
	$\text{FeS}_2 + \text{H}_2 \rightleftharpoons \text{FeS} + \text{H}_2\text{S}$
Ferric iron associated minerals consisting of oxides can undergo reductive dissolution in the presence of hydrogen, where $\text{Fe(III)}$ can be (partially) reduced to $\text{Fe(II)}$ . Hydrogen can also reduce structural $\text{Fe(III)}$ in clays which many alter their structure.	
Hematite:	$\text{Fe}_2\text{O}_3 + \text{H}_2 + \text{H}_2\text{O} \rightarrow 2\text{Fe}(\text{OH})_2$ $3\text{Fe}_2\text{O}_3 + \text{H}_2 \rightleftharpoons 2\text{Fe}_3\text{O}_4 + \text{H}_2\text{O}$
Hydrogen – clay material interactions in argillaceous cap rocks	
	Preliminary studies of hydrogen – clay material interactions also show that retention (adsorption) phenomena could occur in argillaceous cap rocks [43, 44]. These results require confirmation as the measured hydrogen uptakes (up to 0.3 wt% at 50 bar hydrogen pressure and 25 °C) appear to be unexpectedly high when compared to nano-porous materials (e.g., MOFs, Zeolite, activated carbon) specifically designed for UHS and having surface areas two to three orders of magnitudes higher.
Nitrate reduction in the presence of hydrogen and metallic components such as stainless steel, carbon steel and native iron	
	Nitrate may also be reduced to ammonia in the presence of both hydrogen and metallic components: stainless steel, carbon steel, native iron [42, 45] – this latter reaction being relevant only for fluid contact with injection well tubes and casings. Ferrous minerals also seem to be reactive, as suggested by a recent study on hematite reduction to magnetite in the presence of hydrogen at 120 °C [46, 47]. These reactions are likely to decrease the amount of pure hydrogen (e.g., by the production of $\text{H}_2\text{S}$ ).

The scarcity of experimental data has resulted in a lack of agreement in recent publications as to the significance of geochemical reactions in porous underground hydrogen storage. The limited rock types/minerals tested at pressure and temperature conditions relevant to underground hydrogen storage to obtain kinetic rate laws for relevant reactions at storage conditions, typically  $P_{\text{H}_2} = 5 - 20$

MPa,  $T = 30 - 150\text{ }^{\circ}\text{C}$ , along with the lack of a standardized methodology, means the uncertainty surrounding the risk of geochemical reactions during hydrogen storage remains high. In the case of  $\text{H}_2\text{S}$  generation, expected concentrations are significantly lower compared to microbial derived  $\text{H}_2\text{S}$ . Expected concentration ranges at  $T=120\text{ }^{\circ}\text{C}$  are  $10 - 100\text{ ppm H}_2\text{S}$ , which may have an impact on well design, material selection and risk profiles. In addition, the effect of any additional influencing parameters during hydrogen storage (such as the presence of other gases or minerals acting as catalysts, mineral phase and distribution (cement or matrix)) must be investigated over time scales of seasonal hydrogen storage. Therefore, there is a recognized need for further investigations into potential geochemical reactions under site-specific storage conditions, rock/fluid chemistry, temperatures, and pressures. It must also be noted that the verification of potential geochemical interactions in real reservoirs storing pure hydrogen is still insufficient, and not much public data is yet made available. These remain as topics of further developments towards enabling and scaling up the UHS technology.

A key technical barrier to the development of underground hydrogen storage is the significant lack of field scale studies to validate the laboratory and modelling observations. The most established field site is the Austrian Underground Sun storage project, injecting 20% hydrogen into a depleted gas field in Austria for the production of green methane. All other field study sites are at the commissioning stages, as listed below:

- a) Hychico, green methane from hydrogen in a porous reservoir [31]
- b) HyPSTER, 100% hydrogen in a salt cavern in Etrez, in France [27]
- c) H2CAST, 100% hydrogen in salt cavern at Etzel, Germany [28]
- d) HyStock, 100% hydrogen storage in a new salt cavern in Zuidwending, Netherlands [26]
- e) HyBRIT 100% hydrogen in lined rock cavern at Lulea, Sweden [36]
- f) TestUM II, shallow aquifer monitoring testing during hydrogen input tests.

While there has been commercial hydrogen storage in salt caverns operating for decades, there is currently limited sharing of any learnings and field data. Nevertheless, the fact that there has been commercial operation of 100% hydrogen underground hydrogen storage sites for over 50 years suggests that the UHS technology is indeed technically and economically feasible.

### Experimental investigations

So far, experimental investigations of abiotic hydrogen reactions during hydrogen storage in porous rocks and salt caverns are rather limited and published data is often related to nuclear waste disposal or volcanic processes rather than underground hydrogen storage. Therefore, the tested temperatures and pressures do not sufficiently align with those experienced during UHS and as such do not describe the extent to which geochemical reactions might be expected in UHS operations. However, it is still worth noting that high temperature experiments can be very useful to obtain information on kinetic reaction rates that are otherwise very slow - to be extrapolated to lower temperatures. Due to this lack of experimental data at representative storage temperatures and pressures, a wider range of rock types (reservoir, salts, salt interlayers and seal lithologies), as well as the full range of temperatures and pressures encountered during hydrogen storage need to be tested to confirm that any observations of reactivity observed at temperatures and pressures beyond that of UHS are valid. There is also the need to validate the reactivity with hydrogen especially for pyrite in higher temperature reservoirs, where the dissolution of pyrite under reducing conditions and subsequent precipitation of pyrrhotite can be observed at laboratory time scales of weeks to months, at temperatures above  $80\text{ }^{\circ}\text{C}$  and at relatively low hydrogen pressure less than 10 bar [41, 42]. More studies are needed to obtain kinetic rate laws for relevant reactions at storage conditions. The known geochemical reactions that are influenced by hydrogen along with their potential impact on storage integrity, controls on reaction rates, current level of understanding and what we need to know to reduce the uncertainty are summarized in Table A-1 in Appendix A.

### Numerical modelling investigations

The existing evidence gathered through numerical modelling investigations, and not field data, into the geochemical reactivity under hydrogen storage timescales and conditions indicate that there is limited geochemical reactivity. This requires field-data-based validation. Reservoirs with siderite in the formation and high Fe content in formation water have the capacity to scavenge  $\text{H}_2\text{S}$ , in case of microbial or geochemical  $\text{H}_2\text{S}$  formation, and are therefore preferred. Some studies suggest reservoir lithologies that have low levels of carbonate and sulphate-containing minerals and low concentrations of residual  $\text{CO}_2$  will have the lowest risk of geochemical reactivity during hydrogen storage. However, it is important to differentiate whether authors have used chemical thermodynamics (Gibbs free energy), chemical kinetics (rate dependent) or both methods to do their simulations. Some reports indicate a high rate of carbonate dissolution, which is in line with thermodynamic equilibrium, while still the reaction is inhibited by the high activation energy.

A hydrogeochemical model has been created in [48] to identify potential risks associated with hydrogen storage in depleted gas fields. In this model, the conditions specific to a North Sea reservoir were considered and modelled for storage periods of 30 and 300 years. The model uses a reservoir temperature of 40 °C, which is on the low side for a depleted gas field. Most reactions were microbially mediated and limited by  $\text{SO}_4$  and  $\text{CO}_2$  availability. The authors found that after 30 years of hydrogen storage, changes in the mineralogy of the reservoir were minimal, with dissolution and precipitation accounting for a combined porosity loss of 0.05 – 0.21%. This study concluded that when selecting a depleted gas reservoir for hydrogen storage, it should have low levels of carbonate- and sulphate-containing minerals, and low concentrations of residual  $\text{CO}_2$ .

In a later study, the behaviour of the geochemical system in the presence of hydrogen relevant for a specific depleted gas reservoir was studied [49]. The reservoir was in the Molasse Basin, in Upper Austria. To assess gas-brine-mineral interactions, an equilibrium and primary kinetic batch models were constructed, incorporating geochemical data for brine and the sandstone of the gas reservoir. As expected, it was found that hydrogen injection increased the pH value of the geochemical system as the dissolved carbon reacted with the hydrogen. Furthermore, the energy minimization model implied dissolution of primary minerals (muscovite, dolomite, pyrite, ankerite) and precipitation of secondary minerals (anorthite, pyrrhotite, clinocllore and daphnite). The results of the equilibrium model suggested that hydrogen can significantly change the mineral composition of a sandstone reservoir. However, after considering the kinetic parameters, the authors noted that the dissolution and precipitation that occurred in the equilibrium batch models are unlikely to occur on a storage relevant timescale. Still, it was concluded that the possibility of hydrogen loss and influence of reservoir integrity owing to hydrogen-induced abiotic reactions is not entirely ruled out. Given the range of uncertainties, primarily resulting from the absence of reliable kinetic data the results should be viewed as a sensitivity analysis of which possible reactions could happen in the used setting. It should be noted that the reduction of pyrite by hydrogen is not a reaction that is included in a geochemical database currently, nor the kinetic rate of that reaction. Unless a modelling study has explicitly included it, this reaction is not considered in that study.

### Observations from natural hydrogen occurrences in conventional and unconventional reservoirs

The hydrogen molecule has a small size, is extremely mobile and can be rapidly consumed by redox reactions mediated by microbes and/or mineral catalysts. As a result, hydrogen does not accumulate easily in the crust, which led to a misconception that it does not occur freely in the subsurface. However, several recent reviews [50, 51] highlighted that concentrations of molecular hydrogen can be very high (up to 99 vol. %) in a range of geological settings such as ophiolites (oceanic crust that has been uplifted onto continental plates) and associated seeps and in kimberlite pipes (igneous rock, known as a diamond source). Other geologic settings with significant hydrogen occurrences include graphite deposits, volcanic systems, geothermal systems, crystalline basement, potash and evaporite deposits, cataclases (granular fault zones), and anoxic sediments as well as some conventional oil and gas accumulations.

The average concentration of hydrogen in gases from conventional reservoirs is ca. 0.8%, while the median concentration is only 0.01%. However, high concentrations of hydrogen in conventional and unconventional reservoirs have been reported, such as:

- In Australia, for example, 51 – 84% in the Adelaide area within the Gawler Craton and up to 95.3% in the Meda field in the Canning Basin.
- In the Heins and Scott wells in Kansas where 31 gas samples have hydrogen concentrations ranging from 1.4 to 70%.
- Gas with high (98%) concentration of hydrogen were discovered in the Bourakebougou area (Mali).
- A well in Kazakhstan encountered a free water flow with 90-98% of molecular hydrogen in dissolved gas.

Interestingly, a very high concentration of hydrogen of 88.5% (with  $\delta^2\text{H-H}_2 = 742\text{‰}$ ) was reported in an oil-associated gas from the Brent field (211/29-B17) in the North Sea. That gas was unusual because most gases from the Brent field do not contain hydrogen. The high hydrogen was likely formed via artificial processes such as metal corrosion or microbial processes. This has also been observed in Aragon in Spain and highlights how important it is to understand these chemical processes [52].

All of the studies on natural hydrogen are very recent and have not yet progressed beyond the possibility of natural hydrogen exploration. Specifically, they do not yet include any subsurface reservoirs or seeps to study potential geochemical or biological reaction that may occur during hydrogen storage, but they are indeed a perfect field laboratory as an analogue for hydrogen storage in caverns and porous rocks. Next, we provide some site-specific learning points, which are split into porous and cavern systems.

### **Learnings from geochemical reactivity from historic town gas storage sites (porous reservoirs)**

Despite suggestions that town gas storage sites experienced gas composition changes, it is unlikely these are a result of hydrogen induced geochemical reactions, and more likely related to microbial reactions or reactions with  $\text{CO}_2$ . Furthermore, as the sites were operated commercially for many decades, it suggests there is a limited risk to underground hydrogen storage related to abiotic geochemical reactions at the reservoir conditions of these sites. It should be noted that all these sites are operated at relatively low temperature (30 to 60 °C) and the learnings are therefore not necessarily translatable to higher temperature reservoirs.

Experiences from the town gas (containing ca. 50%  $\text{H}_2$ , with  $\text{CH}_4$ ,  $\text{CO}_2$ , CO and  $\text{N}_2$ ) storage sites in Ketzin (Germany), Lobodice (Czech Republic) and Beynes (France) provide some context to the potential significance of geochemical interactions in underground hydrogen storage. However, it is important to consider that CO,  $\text{CO}_2$ , and traces of sulphur present in town gases make them chemically more reactive than pure hydrogen. Therefore, it is not appropriate to directly compare them with the storage of pure hydrogen. However, experience with town gas can indeed provide some useful insights.

A history of experience with the town gas storage in saline aquifers has provided evidence for geochemical and microbial activity during UHS. It is claimed that the concentrations of hydrogen sulphide ( $\text{H}_2\text{S}$ ) produced in Beynes could be qualitatively and quantitatively described by the abiotic reduction of pyrite as opposed to the action of sulphate-reducing bacteria [53]. However, the low temperature of the reservoir (between 50 – 60 °C) makes it more likely that microbial processes were responsible for hydrogen sulphide production. It is suggested that the prevailing hydrogen partial pressure (5 – 10 MPa), temperature (25 °C), and alkalinity at the Beynes storage site support this argument [54]. At Ketzin, gas losses in the order of 200 million  $\text{m}^3$  were observed between 1964 and 1985. The processes causing the gas loss and evolution of gas composition have not been identified but are not considered to be sufficiently explained by microbial degradation alone [54, 55]. Alterations in stored gas compositions were also noted in the town gas storage sites of Ketzin in Germany, and

Beynes in France. Both of these examples are argued to represent abiotic reactions as opposed to microbially mediated reactions.

#### **Learnings on geochemical reactivity from the underground sun depleted gas field storage site**

At the Underground Sun Storage project in Austria, no dissolution or precipitation was observed at the micro-scale during laboratory experiments [56], and no enhanced change in permeability during geochemical flow through experiments with hydrogen conducted on the reservoir rocks was observed.

#### **Learnings on geochemical reactivity from existing salt cavern hydrogen storage sites**

The commercial operation of salt caverns for hydrogen storage spanning five decades suggests that there is a limited risk of geochemical reactivity. How the reactivity is related to the site-specific mineralogy within the caverns needs to be further assessed.

Hydrogen has been commercially stored and operated in three salt caverns in Teesside, Yorkshire, UK since 1972, where one million m<sup>3</sup> of pure hydrogen (up to 95% hydrogen and 3 – 4% CO<sub>2</sub>) has been stored in three salt caverns at about 400 m depth with no reported incidents. An underground hydrogen storage facility is being operated in a salt cavern in Texas in order to enable 'peak shaving' of hydrogen production. This facility is connected to the hydrogen pipeline network that serves Texas and Louisiana for petrochemical requirements. In Germany, in the city of Kiel, manufactured gas containing 60 – 65% hydrogen has been stored at 80 – 160 bar in a 32,000 m<sup>3</sup> salt cavern at a depth of 1,330 m since 1971 [18].

The H2CAST project has begun the first preparatory leak test and material test with hydrogen at the cavern in Etzel, Germany, with 280 kilograms of "green" hydrogen injected into an existing cavern in December 2022 to test the leak proof of both the cavern and the 1 km long borehole [57]. The first results of the test, which lasted several weeks, are promising. However, it is still too early to make any final conclusion, and further investigations and measurements are expected to follow.

#### **Learnings on geochemical reactivity from the HyBRIT lined rock cavern storage site**

HYBRIT has built a pilot hydrogen storage plant (at 100 m<sup>3</sup> expanding to 120,000 m<sup>3</sup>) in Svartöberget, in Luleå, Sweden. The facility is a lined rock cavern, 30 m below ground level, in red granite bedrock, whose walls are lined with cement and steel as a sealing layer. The tests in the pilot storage will take place in 2022-2024 [58], with significant efforts on understanding steel embrittlement.

#### **2.2.3 Conclusion remarks and knowledge gaps of geochemical reactions of underground hydrogen storage**

The available evidence indicates that there is a low risk to the integrity of an underground hydrogen storage site from geochemical reactions. This suggests that reservoir lithologies that have low levels of carbonate- and sulphate-containing minerals, and low concentrations of residual CO<sub>2</sub> will have the lowest risk of geochemical reactivity during hydrogen storage. The scarcity of experimental data, lack of benchmarked models, limited field studies and shortage of publicly available information from commercial hydrogen storage sites has resulted in a lack of agreement in recent publications as to the significance of geochemical reactions in porous underground hydrogen storage. This uncertainty means that the risk from geochemical reactions remains a technical barrier to the development of underground hydrogen storage.

The key knowledge gaps for an improved understanding of the geochemical reactivity of underground hydrogen storage sites include:

- Improved knowledge of pure mineral kinetic reaction rates with hydrogen data encapsulating a wider range of minerals (such as pyrite, pyrrhotite, hematite, calcite and anhydrite, and especially clay minerals which contain a multitude of elements) tested under the full range of



expected storage temperatures and pressures to benchmark and validate modelling software and develop a thermodynamic database on geochemical reactions.

- Validated reactivity of hydrogen with pyrite at temperatures above 80 °C in order to obtain kinetic rate laws and evaluate the potential volumes of H<sub>2</sub>S production.
- Improved understanding of the aqueous phase, its interplay (dissolution, diffusion) with the stored hydrogen. It is important to determine the influence of pressure and temperature on the kinetics of dissolution which governs how much hydrogen becomes available for geochemical reactions, over various time scales. Investigation of the geochemical reactions using different brine salinities is also essential.
- Enhanced investigation of the kinetics of relevant geochemical reactions within the relevant storage time scales. For example, for some thermodynamically viable reactions, one has to investigate if, e.g., reduction reactions with hydrogen can be anticipated within the cycling time frame of a hydrogen storage site.
- Assessment of the dynamic impacts of potential geochemical reactions on reservoir permeability and mechanical integrity of reservoir and cap rocks over time.
- Understanding of potential contaminants in the hydrogen production stream, particularly in porous reservoirs.
- Investigation of fully coupled systems with a wider range of mineral assemblages, fluids and gasses (including cushion gasses) that are more representative of those encountered within the reservoir, to support the development of a site selection methodology, based on lithologies and conditions that mean there is a reduced risk of geochemical reactions during hydrogen storage.
- Standardised methodologies to compare across laboratory and modelling studies.
- Field data for validation of laboratory and modelling outputs.

In summary, there is a recognized need for further investigations at the laboratory, modelling and field scale into potential geochemical reactions and under site-specific storage conditions of rock/fluid chemistry, temperatures, and pressures.

## 2.3 Microbial processes

The subsurface is not a sterile environment and a variety of microbial organisms have been found in rocks many kilometres deep [59]. These include the two major single-cellular groups of Bacteria and Archaea. These deep subsurface microorganisms get their energy from chemical redox (reduction-oxidation) reactions. This requires electron donors (compounds that can be oxidized) and electron acceptors (compounds that can be reduced). Microorganisms make use of "edibles" (electron donors) such as hydrogen, reduced sulphur compounds and ammonium. They "breathe" electron acceptors such as nitrates and nitrites, manganese and iron oxides, oxidized sulphur compounds and carbon dioxide [60, 61]. During hydrogen storage this "microbial biosphere" will be in direct contact with the stored hydrogen and most operating processes will be directly influenced by the activity of those microbes. Molecular hydrogen is considered one of the most important electron donors for microbial respiration in the subsurface, and because of its low reduction potential, hydrogen can be used by many metabolically different groups of organisms [62]. Within their cells, specific enzymes (hydrogenases) catalyse the splitting of hydrogen into protons and electrons, which can be used to chemically store cellular energy [63]. This energy can then be used to drive reactions within the cell, for example CO<sub>2</sub> and nitrogen fixation.

The origin of these microbes in the subsurface can be both indigenous by natural transport or sedimentation processes and can also be anthropogenically introduced by human activity in the subsurface like drilling, pumping or mining. In most cases, short and long-term effects of subsurface operations on the natural communities are not well studied. Storage activities in the subsurface will alter conditions and this will lead to a long-lasting change within the microbial diversity [64].



Microbial growth and hydrogen consumption rates vary with water/nutrient availability (e.g., macro elements C, N, H, P, Ca, Mg, S, Fe and trace elements Co, Mn, Ni, Mo, Cu, Zn) and environmental variables (e.g., temperature, pressure, salinity, pH and naturally occurring growth inhibitors [65]. Each microbial strain is adapted to an optimum set of nutrients and environmental conditions where potentially the greatest growth rates occur. Beyond the optimum conditions, organisms may grow but at reduced rate or they become dormant or even die. It is possible that microbes will re-activate as soon as conditions change back to favour growth. The timespan of possible dormancy is strain-specific, but it is known that some dormant microbes can survive over decades [66].

Assessing the long-term effect of microbial activities on UHS is extremely important as they may impact the feasibility of hydrogen storage through different mechanisms including hydrogen losses through microbial consumption, hydrogen contamination with other gases such as H<sub>2</sub>S, biofilm pore blocking, reservoir damage through mineral precipitation, degradation/corrosion of the operational equipment and potential environmental risks [67]. The conversion of hydrogen into methane (biomethanation) can also be seen as a positive side-effect as methane is more stable and the caloric value of the stored gas is improved [68].

Several known microbial reactions are influenced by hydrogen and listed in Table 2-2.

Table 2-2: Hydrogen influenced microbial reactions.

Hydrogen reaction process	Relevance for the different storage sites
<b>Methanogenesis:</b> Hydrogenotrophic methanogens undergo anaerobic respiration that consume hydrogen and generate methane as the final product of metabolism. $\frac{1}{4}\text{HCO}_3^- + \text{H}_2 + \frac{1}{4}\text{H}^+ \rightarrow \frac{1}{4}\text{CH}_4 + \frac{3}{4}\text{H}_2\text{O}$	Methanogens consume hydrogen and carbon dioxide and generate methane as the final product of their metabolism. They are known to tolerate high temperatures.
<b>Iron reduction:</b> Iron reducing microorganisms interact directly with the rocks in the reservoir to transform Fe <sup>3+</sup> into Fe <sup>2+</sup> generating both aqueous and solid-phase Fe(II)-bearing minerals such as siderite $2\text{FeOOH} + \text{H}_2 + 4\text{H}^+ \rightarrow 2\text{Fe}^{2+} + 4\text{H}_2\text{O}$	Iron (III) reduction relies on the availability of iron oxides and iron-bearing minerals such as smectite and chlorite, as well as the availability of organic carbon, since dissimilatory iron reducing bacteria are strict heterotrophs which synthesize cell carbon from organic compounds. Iron oxides are abundant in many sediments and aquifers but are typically not available in the carbon-rich oil fields because they have been reduced over millions of years and are not replenished.
<b>Sulphur reduction:</b> Sulphur reducing bacteria use inorganic sulphur compounds as electron acceptors to sustain several activities such as respiration, conserving energy and growth, in absence of oxygen. $\text{H}_2 + \text{S} \rightarrow \text{H}_2\text{S}$	The final product of these processes, sulphide, has a considerable influence on the chemistry of the environment and, in addition, is used as electron donor for a large variety of microbial metabolisms.
<b>Sulphate reduction:</b> Sulphate-reducing microorganisms perform anaerobic respiration utilizing sulphate (SO <sub>4</sub> <sup>2-</sup> ) as terminal electron acceptor, reducing it to hydrogen sulphide (H <sub>2</sub> S) $\frac{1}{4}\text{SO}_4^{2-} + \text{H}_2 + \frac{1}{4}\text{H}^+ \rightarrow \frac{1}{4}\text{HS}^- + 2\text{H}_2\text{O}$	Sulphate reduction is a widespread metabolism producing the toxic gas H <sub>2</sub> S. They often need additional carbon sources to grow. Because sulphate reducers may use the same substrates as sulphur reducers (i.e., sulphide and thiosulphate, they are often collectively referred to as sulphur species reducing microorganisms (SSRM) performing sulphur species reduction.

<p><b>Acetogenesis:</b> Anaerobic bacteria produce acetate either by the reduction of bicarbonate/carbon dioxide or by the reduction of organic acids using hydrogen.</p> $4\text{H}_2 + 2\text{CO}_2 \frac{1}{2}\text{HCO}_3^- + \text{H}_2 + \frac{1}{4}\text{H}^+ \rightarrow \frac{1}{4}\text{CH}_3\text{COO}^- + \text{H}^+ + 2\text{H}_2\text{O}$	<p>Acetogens consume hydrogen in the presence of carbon dioxide or organic acids to produce acetate.</p>
<p><b>Aerobic hydrogen oxidation:</b> Hydrogen-oxidizing bacteria use hydrogen as an electron donor. They can be divided into aerobes and anaerobes. The former use hydrogen as an electron donor and oxygen as an acceptor while the latter use sulphate or nitrogen dioxide as electron acceptors</p> $\text{H}_2 + \frac{1}{2}\text{O}_2 \rightarrow \text{H}_2\text{O}$	<p>Hydrogen-oxidizing bacteria use oxygen as an acceptor while using hydrogen as electron donor, as such these microbes will not be of significance for underground subsurface storage, beyond the shallow near well bore environment in case of leakage of hydrogen along the well trajectory.</p>
<p><b>Dehalorespiration</b> by microbes using halogenated compounds as terminal electron acceptors in anaerobic respiration, hydrogen can be used as an electron donor in this process.</p> $\text{Halogenated compounds} + \text{H}_2 \rightarrow \text{dehalogenated compounds} + 2\text{HCl}$	<p>Halogenated compounds are common in aquifers and may arise from contamination or via natural processes in sediments. However, the concentrations of these compounds are extremely low: In aquifers of 170 – 1000 m depth, chloroflourocarbons reach maximum concentrations of <math>\leq 1.1 \mu\text{g L}^{-1}</math> and for pristine aquifers <math>0.003 - 0.007 \mu\text{g L}^{-1}</math> of chlorinated hydrocarbons were measured. It is generally recognized that this process is of low relevance for hydrogen storage.</p>
<p><b>Fumarate Respiration:</b> by eukaryotic organisms where fumarate reductase is the enzyme that converts fumarate to succinate and is a microbial metabolism as part of anaerobic respiration, hydrogen can be used as an electron donor in this process.</p> $\text{H}_2 + \text{fumarate} \rightarrow \text{succinate}$	<p>Literature on the importance of anaerobic fumarate respiration using hydrogen is scarce. In the non-engineered subsurface, readily metabolizable organic matter, like fumarate, is rare and it is generally recognized that this process is of low relevance for hydrogen storage.</p>
<p><b>Denitrification:</b> bacterial reduction of nitrate by hydrogen oxidising bacteria, where nitrate (<math>\text{NO}_3^-</math>) is reduced and ultimately produces molecular nitrogen and hydrogen as an electron donor is oxidized.</p> $\frac{3}{5}\text{NO}_3^- + \text{H}_2 + \frac{3}{5}\text{H}^+ \rightarrow \frac{1}{5}\text{N}_2 + 1\frac{1}{5}\text{H}_2\text{O}$	<p>It is generally recognized that this process is of low relevance for hydrogen storage. Only of concern in nitrate-treated reservoirs.</p>

In underground hydrogen storage sites, as Figure 2-2 illustrates, the most important hydrogen consuming microbes are expected to be methanogens, acetogens, and sulphur species reducing microorganisms (SSRM). Iron reducing bacteria might also play a role, but their activity has not been shown clearly in the field yet [60, 67, 69].

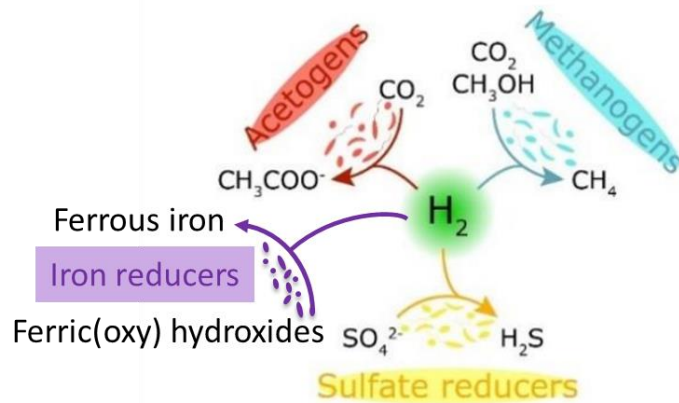


Figure 2-2: Key hydrogen consuming microbial processes [70].

### 2.3.1 Experience of microbial processes from past and ongoing projects and studies

#### Research projects and publications on microbial activity during hydrogen storage

Practical applications or tests with underground hydrogen storage to elucidate microbial processes include underground storage of town gas (50% hydrogen with methane, carbon dioxide, carbon monoxide and nitrogen) as well as the storage of hydrogen with and without carbon dioxide in porous reservoirs and salt caverns. The results from these projects not only give essential information on the question which conversions take place to what extent in practice, but also on the effect of key controlling environmental factors, such as salinity, pH, pressure and temperature.

Evidence collected during experimental investigations into microbial reactivity during UHS is beginning to elucidate the environmental controls on microbial growth, defining critical environmental controls on microbial life limits that can support site selection criteria to minimise the risk of microbial activity. The application of these critical life limits in site selection are described in more detail in Section 2.4.

The environmental controls, sorted after relevance are listed below. Permeability is only relevant for porous rock formations. The other controls are relevant for both porous rock formations and salt caverns.

- **Water:** As the microbes live within the water phase, water availability is key. In caverns water is restricted to the sump liquids (leftover water from that remain at the leaching phase containing insoluble minerals), bottom of the cavern, water on cavern walls and water vapour in the storage volume. In depleted gas fields, water is available as residual water lining the grain surfaces, however during the lifetime of a hydrogen storage complex, repetitive injection cycles of dry hydrogen can lead to the drying out of certain areas of the reservoir especially the near wellbore region. This effect is well documented from natural gas storage and has been described in several papers [71, 72, 73]. The hydrogen dry out effects still needs more investigations in the lab, modelling and field observations.
- **Nutrients:** The nutrient requirements of hydrogen-oxidizing microorganisms are poorly elucidated. Often, only a limited number of single strains within each diverse metabolic group have been investigated, which are unlikely to be representative of all strains. Apart from the primary requirement of water, hydrogen consuming microorganisms require hydrogen as a source of electrons (energy), an electron acceptor and a carbon source for cell division, as well as a set of macro and trace elements and various organic nutrients.
- **Dissolved hydrogen:** As the microbes live within the water phase, they require access to dissolved hydrogen. Given the gas phase injection of hydrogen within a storage system, the equilibrium solubility of hydrogen exceeds the highest threshold value of a hydrogen-consuming microorganism by ca. 3 orders of magnitude at standard temperature and pressure, increasing further with increased pressure. Therefore, it is not expected that a

limitation of hydrogen solubility for microbial growth will indeed occur. However, the kinetics of hydrogen dissolution into reservoir brine are not yet fully understood.

- **Temperature:** Temperatures for underground storage are likely to range between 30 and 150 °C (salt caverns having a lower temperature range of 20 – 60 °C) at a recommended depth range of 500 – 2000 m. Microorganisms are classified according to their preferred growth temperature and the upper life limit of cultivated hydrogen consuming bacteria microorganisms from the published literature is 122 °C [69]. This suggests that the reservoirs with temperatures above 122 °C can be considered sterile to microbial activity, as long as they remain above that temperature during the entire operational lifetime.
- **Salinity:** The relevant salt concentration range for UHS is 0 – 5 M NaCl, at which highly diverse prokaryote communities can be found, and there are halophilic methanogens and acetogens that live in hypersaline environments, up to 4.4 M. There is no upper salinity limit to microbial activity [69]. It appears to be the brine composition (e.g., halite vs carbonate dominated brines), rather than the salinity alone, that can somewhat limit microbial growth.
- **pH:** Brine pH may affect the growth of microorganisms via i) a direct effect on the growth metabolism, and ii) an effect on the redox reaction. Most methanogens and SSRM cannot grow outside the pH range 4 – 9.5. However, eighteen known SSRM are adapted to pH above 10, nine known SSRM grow down to a pH of 1 and six known homoacetogenic strains have critical pH values of 10 pH in the neutral range will favour a higher diversity of microbes.
- **Pressure:** The high pressures encountered in UHS are generally less inhibitory to microbial cellular activity than high temperatures, partly because of the relatively high osmotic pressure of cytoplasm. An upper pressure limit to microbial life has not been established, but at 30 – 50 MPa, the growth of various mesophilic, atmospheric-pressure-adapted microorganisms is inhibited. Very fast pressure changes however will kill microbial cells.
- **Naturally occurring microbial growth inhibitors:** Exposure to hydrogen sulphide,  $H_2S$ , and its bisulphide ion,  $HS^-$ , causes damage to microbial proteins and coenzymes. Threshold concentrations vary from strain to strain.
- **Growth regulation by competition:** Homoacetogenic bacteria often co-exist with SSRM and methanogens, each with their own distinct affinities for hydrogen and growth rates which means they can compete for dominance. In [69] it was found that at low temperatures (ca. 15 °C) and low pH values homoacetogens dominate over methanogens and SSRM. As a general rule pH values below 7 favour the growth of methanogens over sulphate reducers. Above pH 7.5, sulphate reducers grow faster than methanogens and would be expected to outcompete them. With high concentrations of hydrogen, it is possible that multiple metabolisms will be active at the same time. Also, micro-environments can develop in reservoirs where in certain parts of the porous media different metabolic groups might be active.
- **Mineralogy** will directly affect the water chemistry. Buffering minerals like carbonates will stabilize pH and favour higher microbial activity. Minerals are often the source of the macro and micro elements required by the microbes. Surfaces of minerals will often be colonized by microbes, which tend to form biofilms as a protective lifestyle.
- **Permeability** is a factor for microbial life in the subsurface in porous rock formations. In very tight reservoirs going into the milli Darcy range, there is not enough physical space for microbes. Higher permeability reservoirs generally have more microbes [74, 75].

In addition to the experience in managing microbial risk during the storage of town gas, there are two underground hydrogen methanation or biomethanation projects that have provided significant learnings, the Austrian Underground Sun Conversion project and the Hychico project, both injecting hydrogen and carbon dioxide into depleted gas fields aiming for the production of green methane.

#### Learnings from town gas storage in Lobodice (porous formations)

As discussed in the geochemistry section above, experience with town gas (with ca. 50% hydrogen) storage in saline aquifers has provided evidence for microbial activity during UHS. However, as

previously stated, the presence of CO, CO<sub>2</sub>, and traces of sulphur in town gases mean they are far more reactive than 100% hydrogen, particularly as CO<sub>2</sub> is a key requirement in many microbiological reactions. As such, the findings are not directly comparable with the storage of pure hydrogen, but they can provide some useful insights.

For example, consider the town gas storage site in Lobodice, Czech Republic. The unusual behaviour of hydrogen in underground storage facilities has been observed for manufactured gas. Two studies [76, 77] noted changes in the composition of the gas during the injection–extraction cycles and an overall decrease in reservoir pressure at Lobodice [76] where, after being stored for several months. The composition of the extracted gas showed higher methane levels than those of the initial gas. At the same time, the quantity of acidic gases (CO<sub>2</sub> + CO) showed a significant decrease and the observed pressure was systematically lower than the pressure calculated by mass balance. Isotopic analysis of the extracted methane in [77] showed that part of it had a different isotopic signature from that of the injected methane. These different observations justify the assumption of an in-situ generation of biotic methane from hydrogen via the following reaction:  $\text{CO}_2 + 4\text{H}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O}$ . Other observations have revealed further unusual effects, such as the creation of spatially variable zones preferentially enriched in methane or hydrogen.

### **Learnings from the porous rock underground methanogenesis Hychico project (depleted gas field)**

Hychico started a pilot project to produce methane from hydrogen and carbon dioxide by underground controlled methanogenesis. The project has been carried out in collaboration with the French Geological Survey in a depleted gas reservoir located in Patagonia, Argentina. Work commenced in 2010 and focused on investigating methanogenesis processes, as well as the construction of a hydrogen pipeline linking the production and storage sites. This included the biological characterization of the site, identification and optimization of both operational (injection rate, hydrogen – carbon dioxide mix composition, residence times, etc.), as well as the determination of relevant reservoir parameters (temperature, physical and chemical properties of the formation water, etc.) in order to enable the modelling of reservoir behaviour. The two main project objectives behind this were to prove the occurrence of methanogenesis in the reservoir, and to analyse the conditions that promote it. Work has been conducted at the laboratory scale, using site samples and conditions and field investigations, and by means of the injecting a hydrogen, carbon dioxide and methane gas mixture into the reservoir, followed by monitoring of the conditions that lead to green methane production.

The target reservoir is a marine glauconitic sandstone in the developed Golfo de San Jorge Basin in Argentine Patagonia. The reservoir depth is 815 m, with an original pressure of 26.5 bar and a reservoir thickness of 2.5 m, a reservoir porosity of 25%, permeability of 500 mD and temperature of 55°C [78]. The original gas in place is estimated at 750,000 Nm<sup>3</sup>, with a water saturation of 55%.

The project consisted of the injection of pure hydrogen (produced in an electrolysis pilot plant located near the reservoir) and the injection of “Poor Gas”, a mix of carbon dioxide with methane and other gases (35% of carbon dioxide). The working pressure was increased up to 20 bar. Several gas samples were taken during the weeks following the injection to monitor the increasing methane content within the reservoir, with isotopic composition analyses carried out to confirm that the origin of the methane corresponded to methanogenesis. The above outlined field investigations were supported by laboratory studies varying key variables and parameters (such as pressure, temperature, pH, rock composition and initial concentration of gases) in microbial samples, and by monitoring the evolution of gas composition and other characteristics. Physical and chemical parameters that allow the existence (i.e., growth) of microbes and more precisely methanogens, as well as biomass limitation and biological consortia composition, were investigated.

The main results indicate that methane concentration clearly increased throughout the duration of the experiment, whereas hydrogen and carbon dioxide contents decreased. These results suggest that

multiple biological pathways were used to produce methane and that the methanogenesis rate was much slower in the field than those observed in the laboratory. The laboratory studies provided important learnings, including:

- Despite the presence of Archean microorganisms, as well as hydrogen and carbon dioxide, methanogenesis was not always occurring, and was demonstrated as being strongly dependent on the experimental conditions (i.e., rock/mineralogical composition, pH, etc.).
- In the cases when methanogenesis occurred, considerable methane production (sometimes superior to the theoretical rates expected from methanogenesis) was observed within days.
- The influence of rock composition was proven to be a controlling factor for methanogenesis to take place, in particular the presence of calcite was necessary to initiate the process. This dependency was mainly attributed to its buffering properties.
- Methanogenesis was not the only hydrogen consuming mechanism to consider, some reactions involving the consumption of hydrogen without methane production were observed, and generally related to assimilative processes.

### **Learnings on microbiological reactions from the Underground Sun Storage site (depleted gas field)**

During the Underground Sun Storage and Underground Sun Conversion Project in Lehen, Austria, up to 20 vol. %, hydrogen from green sources was mixed with natural gas and CO<sub>2</sub> and stored for a test period of four months [30, 56]. During the first storage period, 18% of the injected hydrogen was not recovered, with a concurrent increase in CH<sub>4</sub> and decrease in CO<sub>2</sub> from 0.2% to 0.05%. This can be linked to the bioreaction of some of the stored hydrogen. Effective permeability slightly increased probably due to a decrease in water saturation. Re-produced fluids showed acetate production of up to 100 mg/L over the withdrawal period in addition to a decrease in sulphate from ca. 20 mg/L to 0 mg/L. However, no H<sub>2</sub>S was reported. This shows that microbial activity was causing at least parts of the hydrogen loss but most likely not all of it, and other geochemical or physical factors were at play additionally.

Data from [56] suggests that different metabolisms were triggered including the activation of microbial methanogenesis leading to CO<sub>2</sub> and hydrogen consumption, showing that already very low amounts of CO<sub>2</sub> are sufficient for methanogens to thrive. Additionally, also acetogenesis and sulphate-reduction seem to have been stimulated. Produced H<sub>2</sub>S was probably scavenged by dissolved iron similar to the results of a previous lab study (from IFA-Tulln, University of Vienna) using the same field water [30].

### **Learnings on microbiological reactions from salt cavern storage**

As with the geochemistry, there is currently limited available data and learnings on microbial reactions in existing hydrogen storages in salt caverns. Similar as in the geochemistry section, the existing successful commercial storage of 100% hydrogen for over 50 years suggests that indeed the UHS technology is technically and economically feasible to be scaled up for the large-scale supply of green energy.

Solution-mined salt caverns are expected to have a generally lower risk of microbial activity during hydrogen storage. A cavern has a much lower surface area than a porous system, which reduces the amount of dissolved hydrogen in the liquid and also the extent of possible biofilm formation. Secondly, the brine and the sump within salt cavern has a very high salinity, which causes osmotic stress in cells leading to highly reduced diversity and abundance [79]. The active hydrogen storage sites (United Kingdom and United States) unfortunately have no available data on performance or potential microbial activity. The matter of fact is that salt caverns do contain microorganisms. The water used for dissolving the caverns and/or the long-term operation may lead to a contamination of the salt cavern that can introduce these halophilic microbes. On the other hand, halophilic microbes might be already present in the salt rock itself [80]. These processes can also introduce dissolved organic matter, which may be utilized as carbon source by microorganisms. Consequently, a decreased diversity in salt caverns does not necessarily lower the risks of microbial hydrogen consumption. There



are currently no published reports (but ongoing studies) of microbial activity in salt caverns used for hydrogen storage. However, a study on the microbial abundance and community structure in five salt caverns currently used for storage of natural gas, but where two of them have a history of storage of hydrogen-rich town gas [81], showed that all five salt caverns were colonized by microorganisms in cell numbers ranging from  $2 \times 10^6$  to  $7 \times 10^6$  cells/ml. Investigated brines had a similar salinity of 4.7 M NaCl and temperatures of 24.5 – 27.9 °C. Several of the detected microorganisms were capable of using hydrogen as electron donor, including *Desulfovermiculus* (SSRM), *Halodesulfoarchaeum* (SSRM), *Acetohalobium* (homoacetogen); however, actively growing (and hydrogen-consuming) species of *Desulfovermiculus* and *Acetohalobium* have not yet been reported at salinities of 4.7 M.

The presence of the *Acetohalobium* and *Desulfovermiculus*, alongside the presence of hydrogen-oxidizing *Desulfovibrio* (SSRM) and *Methanothermococcus* (hydrogenotrophic methanogen), was also reported for a salt cavern used to store oily sand that was operating at temperatures of 40 – 50 °C. The activity of homoacetogens and hydrogenotrophic methanogens was measured at 0 M NaCl and 2.7 M NaCl, where homoacetogenic activity was detected at both high and low salt concentrations, while methanogenic activity was observed with the low salt concentration only. When incubated at 60 °C no microbial activity was detected, regardless of brine salinity.

In summary, what mentioned above means that salt caverns contain microorganisms which theoretically can consume hydrogen. Under which conditions they might be active and whether their activity will be significantly high enough to cause major volumetric and compositional changes is yet to be determined.

#### **Learnings on microbial activity in other subsurface activities**

In the oil and gas industry, reservoir souring and microbially influenced corrosion are well known problems. Various potential countermeasures have been tested, including the removal of sulphate from the injection water, various types of biocides and alternative inhibitors for example nitrate or molybdate. However, the success rates are site specific. One of the major lessons is that for management of souring and microbial corrosion, it is essential to analyse and continuously monitor the relevant geochemical, physical and microbial characteristics of the reservoir. It is worth to be reemphasized that the presence of microorganism in the specific subsurface environment can be considered as a potential for microbial reactivities and thus monitoring.

#### **Impact of hydrogen leakage on soil and groundwater microbial communities (ROSTOCK – H project)**

Gas leakages from underground gas storage sites have been reported regularly. While it can be assumed that Hydrogen will have effects on soil- and groundwater microbial communities and associated nutrient-cycles, in reality there a rapid hydrogen consumption in soils and groundwater. As a result, any hydrogen plume would quickly fade out, while products resulting from associated chemical interactions could become useful tracers for leakage detection [82].

Hydrogen triggered changes in the microbiology of groundwater- and top-soil may also lead to long-term changes in the water- and soil chemistry, which need to be monitored. Within the on-going ROSTOCK-H project first experiments on tracer and specific piezometer measurements have been published to be able to detect potential hydrogen plumes [83]. More of these detailed studies on this important topic are necessary in order to gain more insight on possible environmental effects.

#### **Insights on microbiological inhibition**

Mitigation of microbial activity within hydrogen underground storage sites needs to be specifically assessed in experimental studies. A high range of biocides are available on the market, but they have not been tested on the specific metabolisms of hydrogen oxidation. General biocides like glutaraldehyde are expected to work also on hydrogen consuming microbes. Salt caverns pose a difficulty because of the high salt content in the sump, which can lead to chemical degradation of biocides. Additionally insoluble minerals in the sump might adsorb added chemistries.



Porous media are always difficult to be controlled with biocides due to the very high surface areas and volumes that would require treatment. It is known from the oil and gas industry that if a reservoir starts intense sulphate-reduction, it is extremely difficult to control [84, 85, 86]. Early mitigation and monitoring is preferable and needs to be developed for UHS sites.

Salt caverns as a confined space without significant new input of fresh microbes will be probably easier to control with microbial inhibitors. Still in salt caverns there is the difficulty of the high salt in the sump which can lead to chemical degradation of biocides. Additionally insoluble minerals in the sump might adsorb added chemistries.

### Insights on economic risks and impacts associated with microbially induced hydrogen losses (Hystories project)

In [33] the Hystories project developed cost models of underground hydrogen storage in both salt caverns and aquifers/depleted fields, based on economic losses due to microbiological activity in a “conceptual” underground hydrogen storage project. These processes are highly site-specific, the information presented should not be taken as a reliable result for any given site. It is based on a literature review and lessons learnt from analogues. The likelihood and severity of hydrogen contamination in salt caverns and porous rock storage from past experiences, analogues and modelling works are summarised in Table 2-3 and Table 2-4.

*Table 2-3: Probability and severity of impacts of microbial activity on hydrogen purity in salt caverns. In [87] it is assumed that the losses when storing hydrogen in salt caverns is not significant. There may be a requirement for purification, but its cost is not considered either, as it is judged “negligeable” by one the companies operating a storage, and as the H<sub>2</sub>S production may disappear.*

Reference	Occurrence of noticeable effect of the microbiological activity	Severity when happening	Remarks
Hydrocarbon storage analogue	A few percent of the caverns	Purity question, no product loss	There is no dissolved hydrogen. This is only suggesting that microorganisms can have a noticeable impact at cavern scale
Pure hydrogen storage experience	Unclear, possibly up to half of the caverns	Purity question, no product loss. Purification cost is “negligeable”	There are three salt caverns in the United States (Spindletop, Clements Dome and Moss bluff) and 3 in Teesside in the United Kingdom that are storing hydrogen. Of these caverns, two have had H <sub>2</sub> S detected, without requiring any treatment to be implemented, which was not necessarily due to microbial activity alone.
Modelling and impact assessment up to cavern scale	NA	Purity question, no product loss	Only 1 modelling exercise exists, suggesting a max H <sub>2</sub> S concentration of 0.0024% [38]

Table 2-4: Probability and severity of impacts of microbial activity on hydrogen purity in porous rock store. In [87] it is assumed that 1.5% of the injected hydrogen is not recovered and that gas treatment facilities are required at the outlet of the storage (which is not in the case of salt caverns).

Reference	Occurrence of noticeable effect of the microbiological activity	Severity when happening	Remarks
Natural gas storage	Circa 90%	Purity question or BTEX biodegradation in water, but no product loss	Dissolved hydrogen detectable, was not detected, relevance can be discussed
Town gas storage	100%	From no observation (but contradictory with another publication) to very significant (61% loss)	i) Public information was found for only 3 of the dozen of town gas historical storage sites ii) Published information is partly contradictory on Lobodice and Beynes iii) Town gas mixture includes CO and CO <sub>2</sub> , providing a constant source of carbonate. iv) It is not always clear whether hydrogen was consumed by microorganisms, trapped or escaped.
Hydrogen and natural gas blend storage pilots	100%	Small and decreasing over time (3% in average)	During the Underground Sun.Storage project [30], the injected gas contained 10% hydrogen, but also ca. 0.2% CO <sub>2</sub> , supporting methanogenesis.
Analysis and modelling of the impact up to cavern scale	NA	Negligible to small (<0.01 – 3.2% of the stored hydrogen)	Only 2 recent references, In [69]: < 0.01 – 3.2% In [88]: 0.72 – 2.76%

### Site screening and characterisation of potential UHS sites based on geochemical and microbial criteria

Screening for conditions which create a sterile environment or retard microbial growth is key to storage site selection, and in order to select sites that are at lower risk of hydrogen-loss and damage to equipment from microbial reactions. Temperatures above 122 °C and salinities above 4.4 M are beyond the life limits of known cultured microorganisms (Figure 2-3 and Figure 2-4). Also, the combination of two extremes poses problems for microbial life for example 80 °C at 3 M salinity. As such storage reservoirs that remain at temperatures above 122 °C can be considered at no risk of microbial consumption of hydrogen, with risk increasing depending on the balance of temperature and salinity. However, it is important to note that these studies are all based on cultured microbes and only a few are from subsurface storage locations, so these will change as the knowledge base expands.

#### 2.3.2 Summary of conclusions and knowledge gaps based on the current state-of-the-art knowledge of microbial reactions during underground hydrogen storage

The available evidence indicates that there is a risk of microbial consumption of hydrogen, gas composition changes, biofilm formation and pore clogging and microbial influenced corrosion to wellbores and other infrastructure materials. Data suggests that temperature could be an effective indicator for site selection, with no cultivated hydrogen consuming bacteria surviving beyond 122 °C. However, our current understanding is based on cultivated species, which introduces a number of biases, most importantly that the data is restricted to species that can be cultivated in the laboratory and that the samples are not taken from active storage sites.

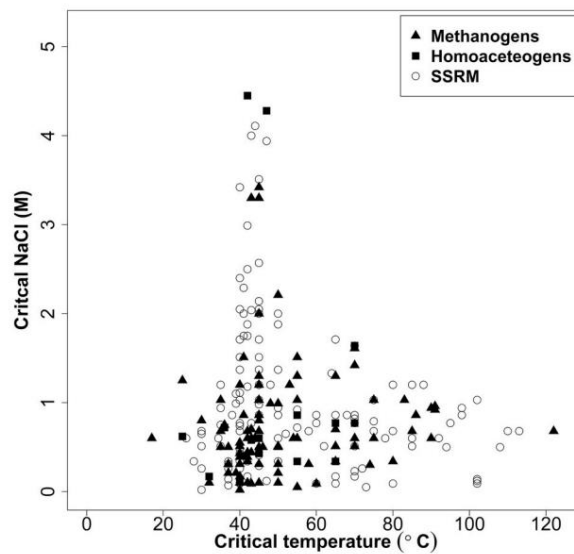


Figure 2-3: Critical temperature (without salinity stress) versus critical salinity, for homoacetogens, methanogens and SSRM [69].

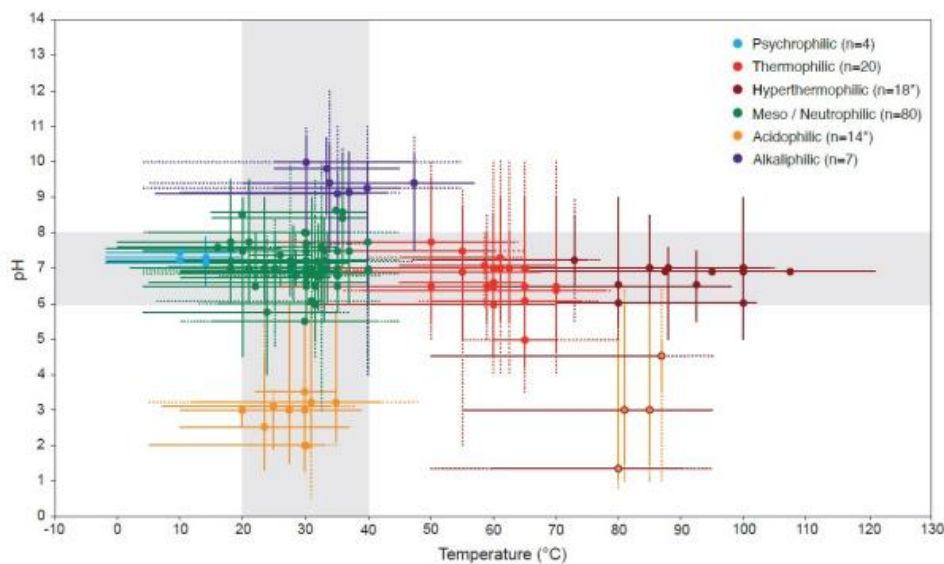


Figure 2-4: Critical temperature (without salinity stress) versus critical pH for iron reducing bacteria [89].

There is a recognized need for further investigations at the laboratory, modelling and field scale into potential microbial reactions under site-specific storage conditions such as rock/fluid chemistry, temperature, and pressure. The key knowledge gaps for an improved understanding of the microbial reactivity in underground hydrogen storage sites include:

- Improved microbial reactivity rates based on microbial experiments using in-situ reservoir water reservoir rock. These need to encapsulate a wider range of host rock types and fluids, or even synthetic laboratory-made brines, tested under the full range of expected storage temperature and pressure conditions to benchmark and validate the modelling software and develop a database of microbial reactions.
- A more comprehensive understanding of the kinetics and thermodynamics of relevant microbial reactions to evaluate what would happen within the various cycles of a hydrogen storage site.

- Experiments under flow-through conditions at pore scale and slim tube scale to simulate reservoir conditions and obtain an understanding of the impacts of dynamic and long-distance flow.
- Improved microbial growth constraints for input into pore scale modelling, to reduce uncertainty and facilitate the development, benchmarking and validation of models using the experimental data to assess field-wide effects.
- The requirement to investigate the impact of microbial communities, rather than individual species.
- The importance to understand interactions between geochemical and microbial reactions and nutrient availability for microbes from reservoir minerals.
- Development of standardised sampling and analytical methodologies to be able to compare across laboratories.
- Mapping out and evaluation of best practices, standards and methods to monitor hydrogen quality and microbial processes in the storage site and near well bore environment.
- Development of standard sampling procedures and guidelines for field trials, which will need to include:
  - Rock/fluid sampling,
  - Sample preparation,
  - Recommended set of analyses,
  - Experimental equipment/processes.
- Field trials and data for validation of laboratory and modelling outputs, with intensive monitoring. In particular, field scale rates of conversion and/or generated contamination and volumes of conversion and/or generated contamination.
- Thermodynamic data for microbial reactions (not well documented so far), which are required to improve the modelling for long-term site management.
- Research on how to stimulate the "right" kind of microbes (for example methanogens when biomethanation is intended) would be valuable for the utilisation of microbes in the subsurface to, e.g., generate biogas.
- Testing of microbial inhibition options and the development of new technologies and methods specific to UHS sites to address the uncertainty around effective inhibition deeper in the reservoir, as microbial inhibition is already relatively easy to accomplish in the well bore and near wellbore environment.
- Develop sensors specifically for the detection of hydrogen underground gas storage reactions.

## 2.4 Impacts on development and operations

Table 2-5 summarizes the key risks from microbial reactions, and whether the risk is technical, safety and/or economic. It is crucial to fully understand and mitigate the risks before a project begins as, once problems occur during operation, mitigation options are usually limited and more expensive. It is also important to consider the following two points:

- The best mitigation option is site selection, taking into account a) type of reservoir (gas reservoir, salt cavern) and b) local conditions (especially salinity, temperature, pressure).
- Currently the risk rating shown below is tentative with a high uncertainty, more site-specific information is needed.

A generic overview of potential hazards and adverse effects is included in Table A-1 in Appendix A.

Table 2-5: Tabulated overview, description, qualitative rating of risk and impact of geochemical and microbial reactions and, possible mitigation strategies.

Hazard or adverse effect	Description	Possible mitigation	Type of risk
Gas mixture change	Microbial activity can lead to a decrease of hydrogen, increase of H <sub>2</sub> S or methane, and increase/decrease of CO <sub>2</sub>	Biocides, Site selection	Technical, safety, economic
Souring and H <sub>2</sub> S formation	Microbial activity can lead to H <sub>2</sub> S formation, a toxic and corrosive gas. Sulphate needs to be present. Enhanced by the presence of hydrogen and easily degradable carbon sources.	Biocides, nitrate, Site selection	Technical, safety, economic
Steel corrosion	Microbially influenced corrosion can occur in environments with active microorganisms. Unknown whether hydrogen stimulates MIC (because of stimulation of microbial activity) or limits MIC (because of offering an alternative electron donor instead of Fe(0))	Biocides, coatings, cathodic protection	Technical, economic
Microbial-induced plugging	Microbial growth will lead to biofilm formation which can cause clogging. Also, mineral plugging can occur upon microbiologically mediated reactions.	Biocides, Site selection	Technical, economic
Dissolution of minerals and change in reservoir properties	Microbial or chemical reactions can lead to the dissolution of reservoir minerals, e.g., carbonate and other easily dissolvable minerals.	Biocides, Site selection	Technical, safety
Hydrogen leakage	Hydrogen leakage from reservoirs into the groundwater will affect groundwater microbial communities and associated nutrient cycles.	Leakage prevention	Technical safety

## 2.5 Summary of findings and recommendations

Hydrogen is a highly reactive element, which is likely to undergo or trigger geochemical and microbial reactions in the subsurface reservoir. There are indications that such reactions may occur both in salt caverns and porous rock formations. The latter is generally considered to be the most challenging setting due to the more complex and heterogeneous mineralogical and fluid composition and inherent uncertainties regarding reaction processes.

There are three main areas which are key to governing geochemical reactions and microbial activity.

### Constraining and preventing reactions with hydrogen

So far, the various reaction processes that may occur in the reservoir as well as the conditions and minerals that trigger these reactions are mainly investigated in isolated laboratory experiments and there is very little data from in-situ (subsurface) observations and measurements. Based on the current knowledge and insights, the following actions are recommended in order to obtain improved

tools which help operators and relevant stakeholders to anticipate, avoid and/or minimize impacts from subsurface hydrogen reaction processes:

- **(Researchers):** Establish a database with test results from multiple geological environments. This will help to expand insights in the variety of conditions in which reactions take place and it stimulates a more common and standardized approach for sampling, analysing and reporting.
- **(Operators):** Determine optimum geological and operational conditions. This will improve the screening and maturation of sites, the design of UHS facilities and the specification of operational parameters.
- **(Researchers, operators):** Quantify coupled processes in dynamic subsurface environment. This is much needed to understand and predict the complex interactions that take place in the real subsurface environment.
- **(Operators, researchers):** Development of a testing framework, and further research, for existing gas storages as these are candidates for hydrogen storage.

### Monitoring of hydrogen reactions

There are sufficient capabilities and tools to perform observations and analyses of geochemical and microbial processes in the laboratory environment. Within the subsurface we can only detect such reactions via indirect indicators of potential conversion (e.g., loss of hydrogen, impurities in hydrogen produced from the storage reservoir).

Following actions are required to increase the ability to observe and assess hydrogen reactions in the subsurface environment and to adequately respond to observed reactions:

- **(Operators, researchers):** Further knowledge, capacities and validations are needed to improve the understanding and modelling of how effects propagate to impacts on subsurface, facility and surface environments. This will help to better predict and monitor reactions in the reservoir.
- **(Regulatory authorities, operators, researchers):** Guidelines and regulations including standards and safety norms must be established in order to define monitoring objectives and benchmarks for responding to observations.

### Mitigation of hydrogen reaction impacts

Gas treatment technologies for removal of impurities and gas contaminations are widely available and applied in e.g., oil and gas production, UGS operations. With some modifications, these technologies and components can also be applied in UHS (see also Chapter 6). Furthermore, existing industry experiences are available for designing and performing operational interventions in response to observed reactions and eventual resulting hazardous incidents.

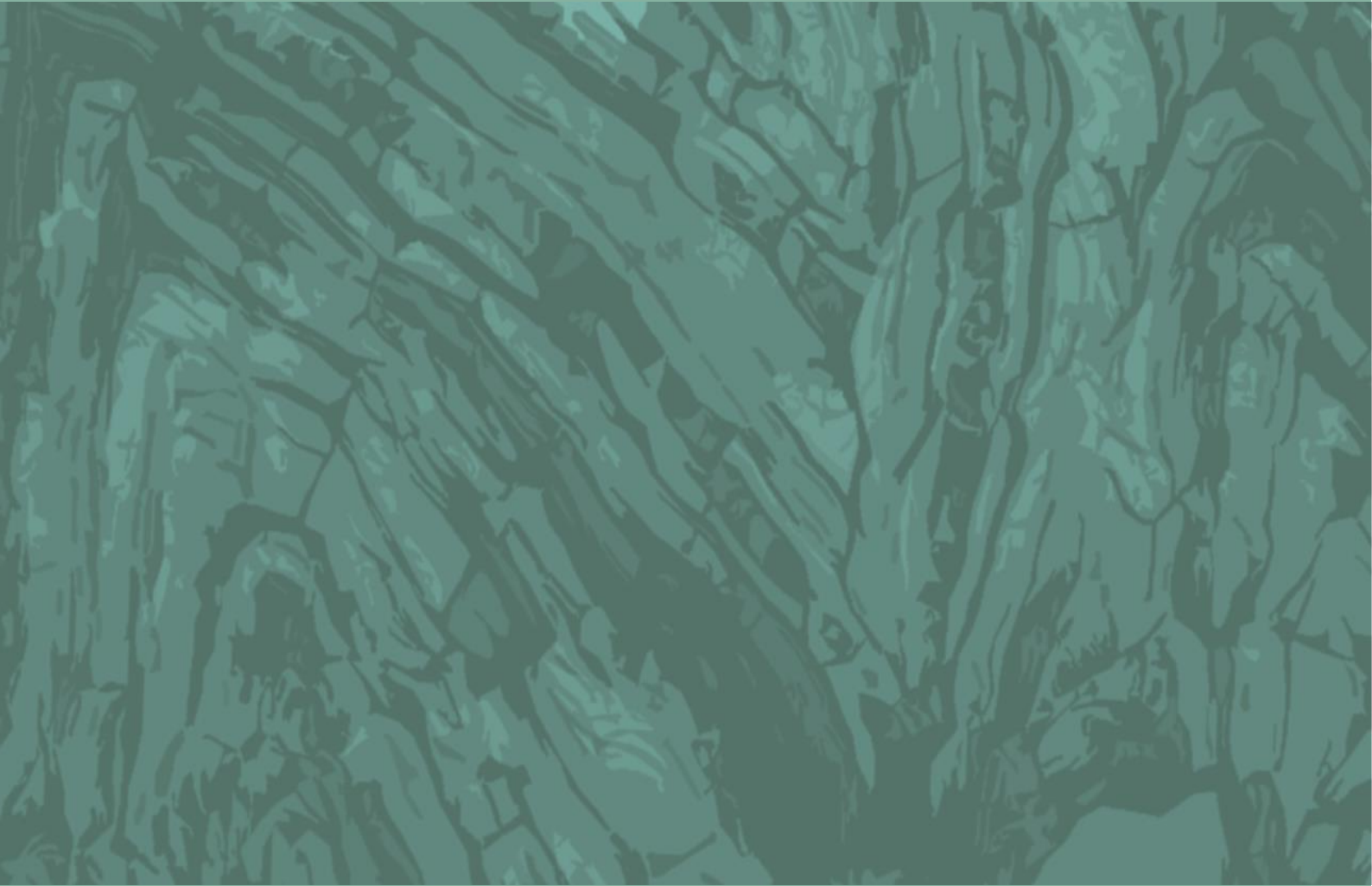
In order to fully prepare and implement mitigation strategies, the following actions are required:

- **(Manufacturers, operators, researchers):** Development of specific sensors, methods and monitoring strategies to ensure that relevant reactions and impacts are detected in time for any mitigation measures to take place.
- **(Operators, researchers):** Improvement of the matching and validation of models with subsurface observations in order to better predict reactions and impacts.
- **(Researchers, operators):** Determination of sensitivities and thresholds for observation of reactions and impacts.



# CHAPTER 3

## Storage Integrity



Hydrogen containment and integrity of porous rock storage

Integrity of salt cavern storage

Geophysical monitoring

Impacts on development and operations

### 3 Storage integrity

#### 3.1 General introduction

The containment and integrity of underground storage sites for hydrogen gas are of vital importance for a safe operation of UHS. On the one hand there is increasing confidence that shale rocks are an effective seal to migration of hydrogen, while homogeneous rock salt has already been proven as a seal in an operational environment [16]. On the other hand, however, substantial knowledge gaps remain in our understanding of the impact of hydrogen on rock mechanical behaviour during cyclic loading. This includes the behaviour and impact on the wellbore (cement) and rock interface, and faults (including fault reactivation and leakage). Therefore, more work needs to be conducted in this area in the future to identify and manage the possible risks, and thus assure the long-term storage integrity during the UHS.

This chapter summarizes the main processes, concepts and gaps related to the integrity of UHS, based on operational experience in UGS and CCS, combined with the (limited) available published research on UHS. It presents the state-of-the-art in understanding of processes and concepts that relate to storage integrity issues in UHS, followed by recommendations to enable UHS demonstration projects with a focus on storage integrity, impacts and bottlenecks associated with site development and operations. Underground hydrogen storage is considered in both porous rock formations and salt caverns. Under prevailing pressure and temperature conditions in these reservoirs, hydrogen will be stored in a gaseous state. For UHS in porous rock formations, this chapter reviews the impact of microbial activity and geochemical reactions on storage integrity, the gas tightness of caprocks, the storage integrity of caprock, reservoir rock, and fractures and on faults during cyclical hydrogen injection and production (Figure 3-1A). For hydrogen storage in salt caverns, the salt cavern stability and integrity during cyclic loading will be essential (Figure 3-1B). More importantly, geophysical and petrophysical monitoring will also be discussed with a focus on in-well and remote monitoring methodologies for long-term safe and efficient operations. Finally, this chapter will provide recommendations for field demonstration projects and implementation for future research.

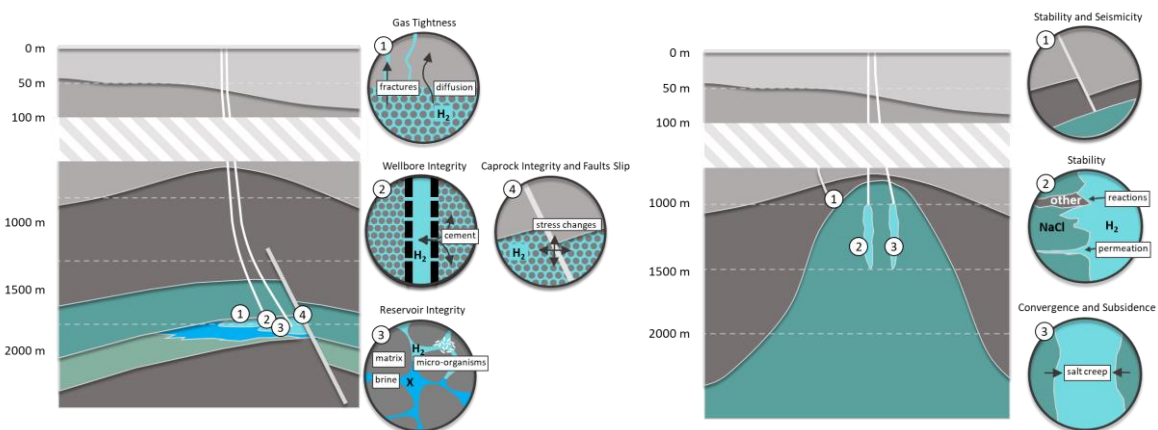


Figure 3-1: A) Schematic diagram highlighting the key areas of storage integrity during UHS in subsurface porous media. Schematic diagram highlighting the key areas of storage integrity during UHS in salt caverns.

Figure 3-2 shows a summary of the main controlling processes, grouped into microbial activity, geochemical reactions and physical processes known to be associated with hydrogen injection and production. Microbial and geochemical activities may lead to microbial growth, mineral dissolution, and precipitation, that in turn can impact caprock, wellbore and reservoir integrity, as well as recovery of stored hydrogen (see Chapter 2 for details). Pore fluid pressure variations due to the hydrogen injection and production will impact the effective stress state in the reservoirs, caprocks and faults.

This process may lead to fault slip and fracture propagation. Faults are referred to as larger-scale discontinuities within the reservoir and/or caprock, which have an offset, such as bounding normal/thrust faults. By contrast, fractures are smaller-scale discontinuities without an offset, such as a fracture network at the base of the caprock.

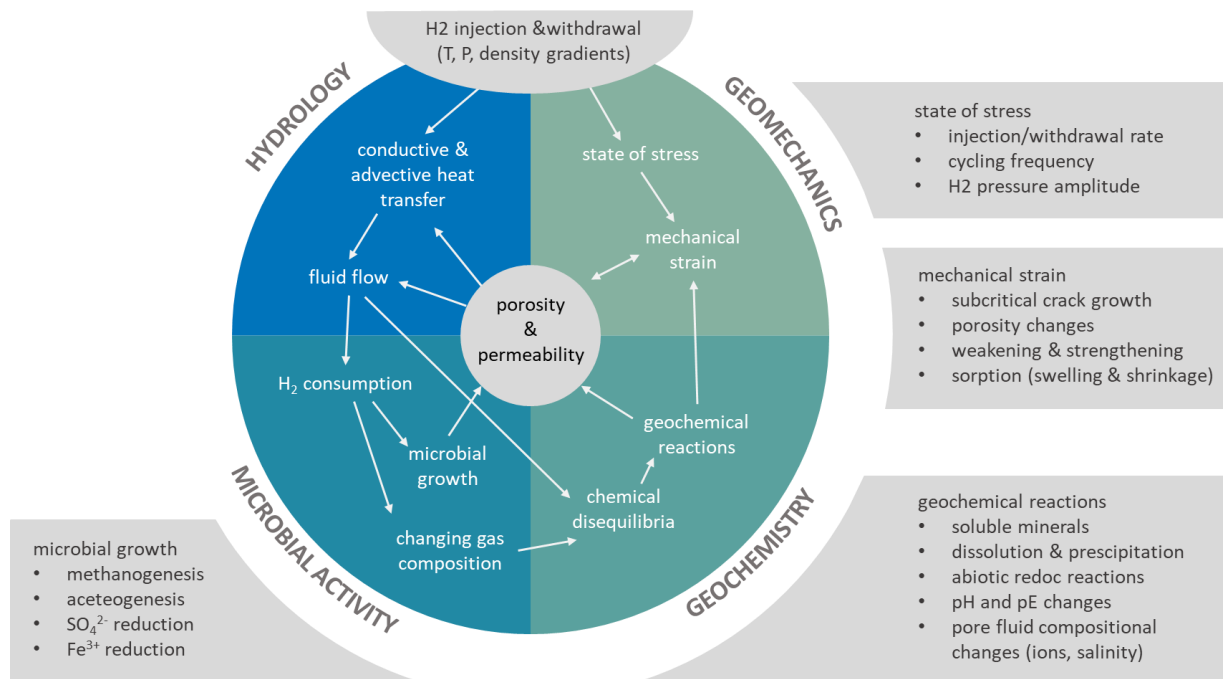


Figure 3-2: Cross-cutting nature of processes and impacts affecting storage integrity during UHS in subsurface porous media. Note that the same workflow applies to salt caverns but with sealing and cavern integrity rather caprock and reservoir integrity. Modified after [90].

## 3.2 Hydrogen containment and integrity of porous rock storage

### 3.2.1 Tightness of intact shale caprocks to hydrogen flow

This section focuses on the tightness and sealing capacity of shale caprocks. Evaporitic caprocks (e.g., halite) are discussed in Section 3.3.

The sealing capacity of caprock is of crucial importance for the containment of injected hydrogen within its dedicated storage reservoir during UHS operations. The long-term containment ability of caprocks with respect to hydrogen is determined by its capillary entry pressure and the thickness of the caprock. Capillary pressure is a function of the hydrogen-brine-shale system wettability and the interfacial tension (IFT) between hydrogen gas and brine. Compared to the wide range of studies on the CO<sub>2</sub> – brine – caprock system for CO<sub>2</sub> storage operations, current research on caprock sealing capacity during UHS is still limited although town gas storage (50% hydrogen) in porous rocks has been successful historically [77, 91, 90, 92]. To maintain an effective barrier, caprock thickness should exceed the throw of any faults that cut [93].

#### Capillary entry pressure

Few direct measurements of the capillary entry pressure of hydrogen in shale caprocks have been performed. The reported contact angle for hydrogen – brine – shale, and interfacial tension (IFT) for brine – hydrogen suggest that intact shale caprocks would be able to act as effective seals against hydrogen flow, due to their high capillary entry pressures of hydrogen into shale [94, 95]. The capillary entry pressure for tested clay-rich caprocks was shown to be 4.9 – 6.3 MPa (711 – 914 psi) [96]. Further measurements and investigation are needed to quantify the breakthrough pressures of hydrogen in shale caprocks experimentally, under realistic in-situ and site-specific conditions.

### Wettability and interfacial tension

Research shows that the wettability of minerals and rocks in the presence of brine and hydrogen is always water-wet (from strong to weak water-wet depending on pressure and temperature). At typical reservoir conditions (50 – 85 °C, 10 – 20 MPa), the wettability of sandstone is weakly water-wet to intermediate-wet [97, 98, 99, 100]. The wettability of calcite is also weakly water-wet to intermediate-wet regardless of temperature and pressure [101, 102]. Similarly, shale caprocks with high clay contents (e.g., kaolinite, illite, montmorillonite) exhibit strong water-wet to intermediate-wet in the presence of hydrogen [103, 104]. Furthermore, the water-wettability of clay-rich caprocks decreases with hydrogen pressure, organic acid concentration and total organic content, while it increases with temperature [94]. Increasing the water-wetting ability of the shale caprock will increase its sealing capacity [105, 106], preventing hydrogen from upward migration, hence avoiding sealing failure during UHS [107].

The interfacial tension between hydrogen and formation brine decreases with increasing pressure and temperature, and with decreasing salinity [98, 106, 108, 109, 110]. Overall, the IFT varies from 45 to 80 mN/m [95], which is slightly greater than the IFT of brine – methane (from 30 to 60 mN/m), depending on pressure, temperature, and brine composition.

### 3.2.2 Diffusion and dispersion of hydrogen through shale caprocks

Hydrogen losses due to diffusion will mainly be focused on upwards dispersion of hydrogen through the caprock, which will take place even through intact shale caprocks. However, research show that such dispersion will have a minor impact on hydrogen loss [48, 111].

Although hydrogen has a higher diffusivity than methane in pure water at 25 °C ( $5.13 \times 10^{-9} \text{ m}^2/\text{s}$  for  $\text{H}_2$ ,  $1.85 \times 10^{-9} \text{ m}^2/\text{s}$  for  $\text{CH}_4$ ), the diffusion rates change when the tortuosity and chemistry of porous systems are considered [48]. Effective diffusivities for hydrogen (i.e., hydrogen saturated with water) at 25 °C are reduced to about  $3.0 \times 10^{-11} \text{ m}^2/\text{s}$  in clayey rocks, or about an order of magnitude lower than methane under similar conditions ( $2.35\text{--}2.49 \times 10^{-10} \text{ m}^2/\text{s}$ ) [48]. This in part accounts for the minor impact of hydrogen dispersion through caprock on hydrogen loss.

### Laboratory measurements of permeability and diffusion rates

Laboratory measurements of hydrogen permeability and diffusion rates were reported by [96], who measured relative hydrogen permeabilities in water-saturated clayey Callovo – Oxfordian caprock. The obtained hydrogen relative permeability was in the order of  $5.5 \times 10^{-23} \text{ m}^2$  ( $5.6 \times 10^{-11}$  Darcy), and not sensitive to temperature.

### Reactive transport: coupled hydrogen diffusion and chemical reactions

While the effective hydrogen permeability of the caprock is larger than that of methane by up to 70% under reservoir conditions [112], reactive transport modelling shows that hydrogen only affects the first few metres of the caprock. For example, the one-dimensional reactive mass transport model in [48] shows that a depleted gas reservoir filled with ca. 95% hydrogen will lose hydrogen only into the lowermost 1 – 4 m of caprock over a 30-year period. In this model, reaction kinetics, changes in mineralogy, microbial methanogenesis, and related changes in porosity were considered and modelled. Similarly, the 3D reservoir model by [113] shows insignificant diffusion losses of hydrogen through caprocks.

### Hydrogen sorption: coupled hydrogen diffusion and sorption

It should be noted that the diffusivity of hydrogen through clay-rich rocks may be further impacted by time-dependent swelling of clays or organic material in the caprock (e.g., smectite clays or coal), through coupled stress – strain – diffusion [114, 115]. The amount of swelling, or sorption, depends on the temperature and pressure of the system, the stress state on the system, the water activity and the sorbing fluid [116]. Since under in-situ conditions, the material is inhibited from swelling due to

the surrounding rock masses, sorption-induced swelling will therefore lead to the closure of pore space, such as cracks and fractures [117, 118], and the generation of a so-called swelling stress. The former can have a positive effect by reducing the permeability of the sealing formation, whereas the latter could potentially lead to self-fracturing [119]. Because sorption-induced swelling is a reversible process, upon hydrogen production desorption will occur and the material will shrink, potentially opening leakage pathways again. The stress – strain – sorption behaviour of swelling clays and organic material has not yet been studied yet for hydrogen under in-situ temperature, pressure, and stress conditions. Recent, unconfined, measurements showed that the hydrogen sorption capacity of montmorillonite [44] is comparable to that of CO<sub>2</sub> [120]. This suggests that similar swelling strains and stresses can be expected during hydrogen injection and production as during CO<sub>2</sub> storage, and the effect of hydrogen sorption on sealing integrity should be investigated.

Existing experimental work and simulation results show negligible hydrogen loss through dispersion in the caprock. More quantitative experimental work, however, remains to be carried out to further expand the current level of understanding. An important area of focus should be the impact of geochemical reactions on mineral dissolution and precipitation, and hence petrophysical properties such as permeability, porosity and tortuosity. In turn, how such processes affect the effective diffusion and dispersion coefficient of hydrogen in shaley caprock, capillary entry pressure needs to be assessed through experimental measurements.

### 3.2.3 *Hydrogen geochemical reactions on caprock integrity*

Only few direct experimental studies have been conducted to understand the impact of hydrogen on caprock mechanics through triaxial tests in the presence of hydrogen. This section presents what is mainly known from publications focussing on the geochemical point of view, which suggest that hydrogen has a minor impact on fluid – rock interactions, and hence integrity will likely not be affected by dissolution – precipitation reactions.

Geochemical kinetics modelling was carried out for shale minerals, and the results confirm that hydrogen – brine – shale interactions cause negligible mineral dissolution and precipitation over 30 years [121]. However, given that hydrogen dispersion in low-permeability caprock will be extremely slow [48], hydrogen-induced geochemical reactions with kinetics should be expected to play only a minor role in affecting caprock integrity.

Following knowledge gaps have been identified that need to be addressed in the future:

1. While the geochemical experimental and numerical modelling work discussed above suggests minor effects, these experiments were not performed at reservoir pressure and temperature conditions. It is important to test rock mechanical properties experimentally in the presence of hydrogen at reservoir conditions of pressure and temperature using triaxial tests. The timescale of such tests will not bring forward any mechanical changes induced by dissolution/precipitation reactions, yet they will show effects of fluid-assisted processes, such as physicochemical reactions and subcritical crack growth.
2. Given that geochemical processes are time-dependent, to model their effects on long-term storage integrity, geochemical experiments need to be carried out in which reactions are accelerated, for example by increasing temperature, reaction surface area, or driving forces. This would require X-ray transparent triaxial cells with high resolution, for example, synchrony X-ray. The condition is that at these enhanced conditions, the reaction proceeds in the exact same way as under in-situ PT conditions. Increasing temperature is not a perfect solution. However, it is an option to accelerate the geochemical reactions through high temperature. This is also dependent on what hypothesis is being tested. When related to mineral dissolution and precipitation, increasing temperature would be helpful. If it is related to surface energy associated subcritical crack growth, increasing temperature might not help much.



3. Shale caprocks are often rich in organic materials and edge-charge minerals. The interactions between hydrogen and organic materials and edge-charge minerals, and how these interactions may impact caprock mechanical properties and permeability during long-term UHS, need to be studied. Such studies should identify interactions, but also consider their kinetics to ensure long-term storage integrity.

### 3.2.4 Reservoir Integrity

Experimental data on the impact of hydrogen on reservoir rock mechanics and its stability and integrity is sparse, in particular under cyclic loading. Although a natural hydrogen shallow gas field has been documented in Mali without obvious integrity issues [51], more data from lab-scale to field scale needs to be provided to de-risk the long-term reservoir integrity and stability during UHS.

Chapter 2 investigates the various geochemical processes that may occur as hydrogen is injected in underground formations. Based on the limited experimental [122] and numerical modelling studies on geochemical interactions [48, 88, 121, 123] it can be concluded that geochemical reactions can lead to minor mineral precipitation and dissolution mostly in reservoir rocks containing carbonate, sulphate, sulphide, and ferric-bearing minerals. Whether these mineral reactions impact the strength and elastic properties of the reservoir rock will depend on their extent (i.e., porosity change) and whether the load-bearing framework is impacted.

In addition to above-mentioned dissolution and precipitation processes, the presence of hydrogen in the rock – brine system may affect the geomechanical properties of the reservoir rock matrix. The following overview summarizes several processes for which there are still major knowledge gaps and which need to be addressed in future research and tests in order to enable field demonstration and deployment of UHS:

1. The impact of geochemical reactions on rock strength and elastic properties needs to be experimentally quantified through triaxial tests with presence of hydrogen, in particular, for reservoirs with presence of carbonate, sulphate, sulphide, and ferric-bearing minerals over 5 wt% [88].
2. Similar to hydrogen-induced dissolution/precipitation reaction, addition of hydrogen to the brine-mineral system may lead to increased stress-enhanced dissolution-precipitation creep (pressure solution creep [124]).
3. The impact of hydrogen-brine-mineral interactions on subcritical crack growth. Since hydrogen injection and associated mineral reactions change the pH of the pore fluid, the interaction between water molecules and crack tips may be impacted. Furthermore, hydrogen itself may interact with the chemically active bonds at crack tips. This could result in weakening of molecular bonds, possibly enhancing time-dependent (subcritical) crack growth, and hence grain breakage.
4. Experimental results indicate that up to 0.11 wt% of hydrogen is adsorbed on the clays at 90 °C under 0.45 bar of relative pressure [43]. Although this indicates that sorption of hydrogen onto clays is expected to be minor, these effects may need to be further quantified. Intergranular clay swelling/shrinkage-cycles could lead to progressive fatigue of the reservoir. In addition, if the water content of the intergranular clay changes over time, e.g., due to drying caused by the cyclic injection-production of dry hydrogen, then the impact of sorption will change over time, as swelling is controlled by degree of interlayer water.

### 3.2.5 Fault stability and fracture network evolution

To assure the storage integrity during cyclic loading of hydrogen, it is important to avoid fault slip and fracture propagation due to frequent in-situ stress variations. Similar to reservoirs and caprock, there are clear gaps in our understanding of how fault frictional behaviour may impact the long-term integrity of storage sites during UHS, and how faults may be further impacted by hydrogen – brine –



mineral interactions. This section presents what is mainly known from the limited data available, and industry experiences in UGS and CCS.

### **Fault frictional behaviour**

Minerals that can react with hydrogen through redox reactions, such as carbonates, sulphates, sulphides and  $\text{Fe}^{3+}$ -oxides, may be present on the surfaces of faults. When these minerals react, this can cause reductive dissolution, which can then extend existing microfractures along the main fault plane and its surrounding damage zone [125]. Subsequent changes in in-situ geochemical properties may also lead to the secondary dissolution of other minerals, such as illite and kaolinite, where the kinetics of dissolution are strongly pH-dependent [126, 127].

In addition, fault frictional properties can be impacted by chemical reactions if they cause a substantial change in mineralogy in the fault gouge (i.e., replacing frictionally ‘strong’ minerals by ‘weak’ minerals, such as clays; precipitation of carbonates or sulphates, which are ‘seismogenic’ minerals, or affecting the degree of cementation). The extent of such reactions will strongly depend on the availability of fluid (hydrogen but also water).

Furthermore, the adsorption and desorption of hydrogen onto swelling clays [43, 128] can lead to swelling-induced stress changes that may impact fault behaviour and integrity and thus potentially compromise storage integrity [119]. Therefore, additional lab research and monitoring data from field demonstrations are required to quantitatively address the impact of hydrogen-induced stress-strain-sorption effects on fault stability during UHS.

### **Reservoir deformation and associated fracture propagation in the caprock**

Reservoir deformation will be highly dependent on formation depth, overburden, underburden, tectonic setting, rock type and regional stress field. Cyclical variations in the stress-state change induced by the injection and withdrawal of hydrogen may lead to deformation of both reservoirs and caprocks. In the reservoir, hydrogen cycling will periodically change the pore pressure, and hence the effective state of stress in the matrix, even in parts of the reservoirs not directly affected by the hydrogen and cushion-gas plume, [90, 129]. The rate at which the effective stress is then changing, is thus directly coupled to the rates of hydrogen injection and withdrawal. Such changes in effective stress could then lead to irreversible reservoir deformation, which in turn could compromise storage integrity [130, 131]. Permanent deformation in the subsurface could also lead to permanent subsidence at the surface [132].

For the caprock with pre-existing fracture network, cyclic changes in the stress regime can induce tensile and shear damage [130, 133, 134], given the migration of hydrogen. Although this type of rock failure is caused by stress changes, fracture propagation can be affected by the availability of hydrogen-rich hydrous fluids at the crack tip, or even the refresh rate of such fluids at the crack tip. When fracture propagation is much faster than the fluid propagation, or if the fluid does not get refreshed fast enough, this will impact the ability for the fluid to interact with the stressed bonds at the crack tip [135, 136]. Depending on the injection and withdrawal rate, the fluid at crack tips may or may not become sufficiently replenished or will become trapped, which will impact the rate and extent of fracture propagation [137, 138]. This could then result in a loss of caprock sealing capacity, allowing the stored hydrogen to migrate upward, and out of the storage container, which would strongly impact the successful operation of any UHS project.

Currently, most of our experience with reservoir and caprock deformation driven by cyclic stress-regime changes comes from underground (natural) gas storage projects. For now, it is unknown whether the presence of hydrogen will significantly affect the mechanical behaviour of the reservoir and caprock compared to natural gas. Therefore, more detailed studies need to be conducted to quantify the effect of stress-regime change on reservoir and caprock deformation, and on fracture generation and propagation in the presence of hydrogen.

### 3.3 Integrity of salt cavern storage

Salt caverns have been proven to maintain their mechanical integrity over the lifetime of at least several decades in applications for underground gas storage (among others [139]), Compressed Air Energy Storage (CAES) [140] and Underground Hydrogen Storage [35, 141]. From a geomechanical point of view, the high compressive strength of rock salt ensures that the cavern geometry remains stable over the lifetime of a storage cavern, while rock salt creep has the potential to heal operation-induced fractures depending on the presence of aqueous fluid films [142, 143].

#### 3.3.1 Hydrogen cyclic loading impacts on salt rock mechanical properties

The rock mechanical properties, and viscoelastic and viscoplastic behaviour of rock salt have been studied extensively in the context of nuclear waste storage [144, 145], and underground gas storage [146]. Experience from the small number of existing hydrogen storage caverns has shown that although hydrogen is a relatively small and reactive molecule compared to natural gas, the mechanical integrity of the cavern is not significantly affected by hydrogen [16, 35, 141]. The operational envelope for safe storage operations in a cavern is established based on geomechanical and thermodynamic assessment. This methodology is independent of the fluid stored, and therefore applicable for hydrogen storage too. Extensive research has been performed in cavern design and operations [147].

However, existing storage caverns are used for long-term storage (i.e., production cycles of months to years) of hydrogen as an industry feedstock [148], or the seasonal storage of gas. Storage and production cycles of 'green' hydrogen for the purpose of power supply is expected to be closer to a diurnal time scale resulting in a higher frequency of injection/production cycling [149, 150]. There is operational experience from natural gas storage operations as to how higher-frequency pressure and temperature changes affect long-term cavern integrity, and which may also be valid for UHS. There is, however, a wide body of published research on the experimental behaviour and constitutive and numerical modelling of salt caverns for high-frequency loading and unloading for CAES, UGS and UHS systems. Although the physical properties of hydrogen, natural gas and compressed air are different, the pressure and temperature cycling timescales that cavern walls are exposed to are similar. In the context of storage integrity, studies on CAES and UGS are therefore also reviewed. The term 'cyclic' in this section refers to the timescale of CAES, UHS and some UGS systems, i.e., diurnal to monthly cycles [140, 148, 151].

Creep behaviour of salt is generalized into three stages of primary (transient), secondary (steady state) and tertiary (accelerated) creep [152], with the microstructure of the rock salt playing a key role in its control. The physical mechanisms impacting creep have been studied extensively and can be categorized as grain size-independent dislocation creep and grain size-dependent, stress-induced dissolution – precipitation creep [144, 153, 154, 155]. Different constitutive models have been proposed to capture the viscoelastic behaviour of creep stages, often characterized using power-law functions [156].

Cyclic loading of rock salt shows strain – time curves with similar distinct creep stages (see Figure 3-3, [157]). During such load cycles the fatigue limit becomes important [158]. This limit represents a maximum stress threshold beyond which the rock salt shows visco-plastic deformation [159]. Fatigue-related strain rates have been found to increase with increasing maximum stress, increasing loading frequency or loading rate, and a decrease in minimum stress [160]. As some of these parameters are dependent on each other, the cycling loading problem can be reduced to three independent parameters (Figure 3-4): The stress state, described by the mean stress and stress amplitude, and the cycling frequency.

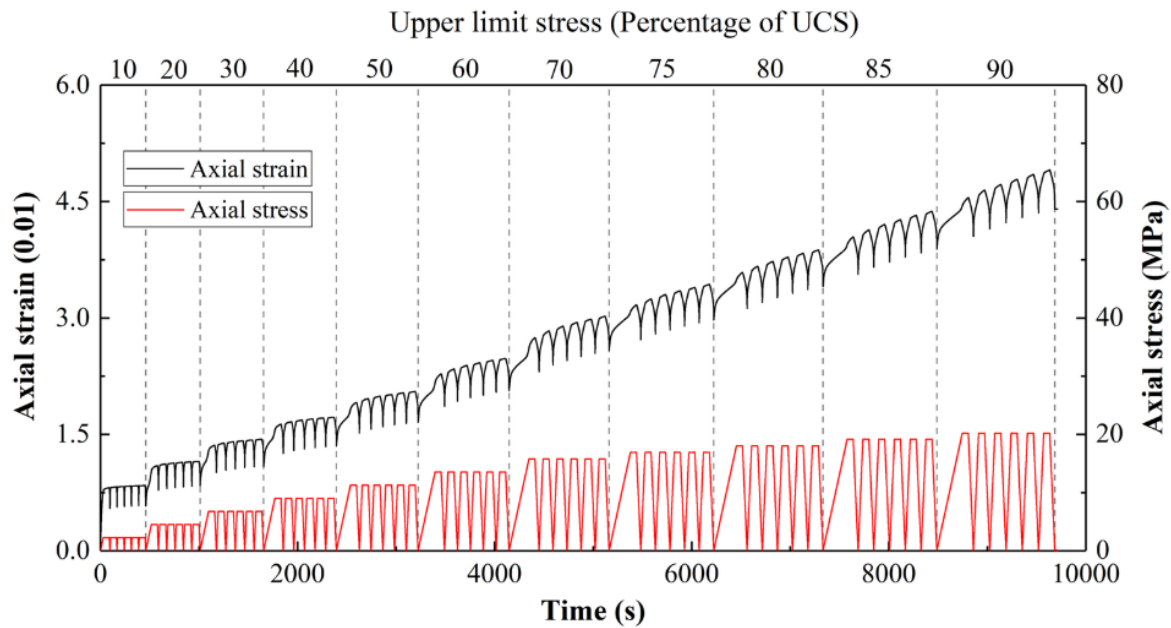


Figure 3-3: Stress-time (red) and strain – time (black) curves for a cyclic loading experiment of rock salt with varying upper limit stresses per cycle [161].

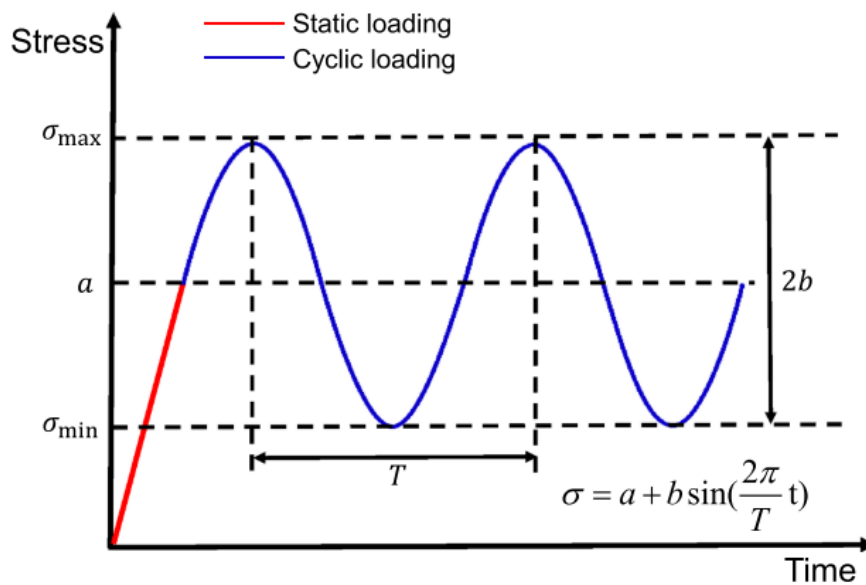


Figure 3-4: Schematic overview of the main variables for pressure cycling in caverns: mean stress  $a$ , stress amplitude  $2b$ , and frequency  $T$ , [162].

Tertiary strains, which are associated with accelerated creep, increase with increasing mean stress, associated with increasing dislocation creep under higher stresses and stress fluctuations [163]. In [164] it was also found that strains increase with increasing stress amplitudes, which is linked to enhanced crack propagation and dilation. Decreasing the loading frequency is also seen to increase strain, as longer steady-state pressure intervals in between cycles increase creep [165]. It is furthermore observed that cyclic loading causes strain hardening resulting in more ductile behaviour compared to static loading, which in turn contributes to the onset of fatigue failure [166].

The integrity and efficiency of hydrogen storage in salt caverns depends on the impact of hydrogen pressure cycling on creep and damage/permeability development in the cavern walls, i.e., on the magnitude and frequency of the injection – extraction cycle. A high confining stress during loading

may affect rock salt deformation via dislocation creep (i.e., in the intact rock salt surrounding the cavern). However, near a cavern wall deviatoric stresses (i.e., the difference between principal stress and hydrostatic stress along all three axes) will be high, while mean stresses are low. Under such stress conditions, crack opening and dilation in the rock salt directly surrounding the cavern and the formation of a damage zone of up to several meters in width will occur [167, 168].

Cyclic changes in cavern pressure will cause changes in radial stress and pore pressure hence effective stress. Therefore, the withdrawal rate of gas from a cavern controls the extent of dilatancy in the cavern wall. The stress conditions under which rock salt becomes dilated, and hence permeable, is described as the 'dilatancy boundary' [169].

As such, cyclic changes in cavern pressure can potentially result in progressive damage development in the cavern wall, and therefore dictate the operating limits. At the same time, damage development in the cavern wall will be coupled to progressive penetration of hydrogen into the surrounding damage zone and the intact rock salt beyond, which eventually may lead to communication with neighbouring caverns and over-/underburden formations. Furthermore, if cavern pressure becomes too high hydraulic or shear fracturing may occur at the cavern roof, leading to potential leakage pathways to overburden formations. To date, a pressure window between 30 – 80% of the lithostatic pressure is suggested as a safe range for UHS, with a maximum cavern depth down to 1500 – 2000 m [35]. However, these predictions neglect the importance that the effect of pressure cycling will have on salt creep and cavern wall porosity – permeability development.

It should also be noted that over time, the cavern may slowly creep, due to the ductile nature of the rock salt and the high stresses at the bottom of the cavern. Recent work has shown that creep closure of a cavern could be associated with surface subsidence, controlled by linear creep in the surrounding, far-field salt [170]. In case of a brittle overburden, slip along pre-existing faults, and potentially induced seismicity, could be an additional consequence [171].

### 3.3.2 Hydrogen geochemical and physical impacts on rock salt mechanical properties

In terms of geochemical reactions, salt rock is regarded as inert in the presence of hydrogen [172]. One of the concerns when it comes to hydrogen operations is the embrittlement observed in metal installations, such as well-casing caused by hydrogen contact. The permeation of hydrogen into metals occurs through an ionisation process that produces hydrogen protons  $H^+$  [173]. Because the size of a hydrogen proton is much smaller than the distance between atoms of the metal lattice, hydrogen can permeate the crystal lattice and cause embrittlement [174]. However, the same process is not to be expected when it comes to salt rocks. First, the ionisation process does not occur on the salt surface since it does not have as many free electrons available as in the case of metals, thus hydrogen protons are not produced. Additionally, as pointed out in [175], atom percolation cannot occur as well because the atomic space in the salt lattice of halite is of 34 pm, while the hydrogen atom size is of 106 pm.

Hydrogen percolation into the salt formation, however, can occur. The cycling magnitude and frequency, and the evolution of the mechanical and transport properties of the salt, will determine the extent of hydrogen penetration and of the damage zone. However, it is unclear how hydrogen penetration will impact its mechanical behaviour. One effect to be expected due to the presence of hydrogen is desiccation [176], which might impact water-assisted mechanisms such as recrystallization and pressure solution creep [154], but also crack healing [143].

After penetration of hydrogen into the damage zone, hydrogen molecules may become trapped in the damage zone or (near) within the intact rock salt during high-frequency cycling [141]. This could lead to over-pressurisation during extraction, enhancing the extent of the damage zone [177]. If the cavern wall is directly exposed to hydrogen, dissolution of (part of) the residual brine water, present in the damage zone, into the initially dry hydrogen phase would lead to subsequent drying out of the damage zone upon extraction of the now wet hydrogen. On the one hand, this drying out could lead to

desiccation fracturing [150], although the presence of connate water could limit the direct contact between hydrogen and rock salt [91]. On the other hand, the removal of water from the damage zone may also affect the contribution that fluid-assisted mass transfer processes could have on crack healing. Desiccation and shrinkage of clay impurities could also affect damage and permeability development. The impact that 'drying out' may have on the mechanical behaviour and transport properties of the cavern walls has not been explored.

### 3.3.3 Thermal effects on rock salt mechanical properties

Given the relatively shallow depth of UHS salt caverns, i.e., between 1,000 – 1,500 m, the temperature difference between the hydrogen and the cavern is not expected to be significant. Still, for each specific scenario, it is necessary to quantify the cavern and hydrogen temperature ranges, specially considering the temperature fluctuations during compression and decompression of injection withdrawal steps [16, 178]. In the case of a considerable temperature difference, one has to include thermal stress along with the mechanical stress for reliable stability analyses and safe operations.

### 3.3.4 Hydrogen reactions and impacts of salt impurities

Though halite itself is chemically inert to hydrogen, some of the impurities that can be present in the evaporite sequence may not be. If the halite is laced with clay impurities, sorption of hydrogen to the clay particles would lead to cyclic swelling and shrinkage (see Section 3.2.2), which may impact crack growth in the damage zone. Similarly, the dissolution of anhydrite could lead to an increase in porosity, which may further impact hydrogen penetration into the damage zone. Effects of compositional heterogeneity of the salt (e.g., anhydrite or clay content) have also been largely neglected to date, but could play a role in damage development [179]. Furthermore, such heterogeneities could possibly trigger geochemical reactions with the hydrogen although there is very little information or experience on this (see Section 2.2.2).

## 3.4 Geophysical monitoring

Geophysical monitoring might be used as a tool to monitor storage integrity of porous rock UHS storage. No monitoring of underground hydrogen storage has been reported in the public domain. However, experience from existing monitoring methods for hydrocarbons exploitation and storage and CO<sub>2</sub> storage remains relevant for underground hydrogen storage. It is worth noting that evaluation of the integrity of the caprock, the reservoir, and the wellbore requires high-resolution data, which can be obtained using geophysical and petrophysical methods in wells and/or at the surface.

Learnings from UGS and CCS are given below.

1. In the case of storage in depleted gas reservoirs, geophysical and petrophysical data with sufficient resolution of the reservoir and caprock will most likely be available. Also, any faults in the vicinity would be known from the exploitation phase of the field. In the selection procedure for UHS proof of non-seismicity of reservoir is required. It is therefore important to perform passive seismic measurements with seismic stations installed in a dense surface array and/or at sufficient depth in boreholes for at least several months before the start of underground hydrogen storage to gather information about the local seismicity, i.e., baseline measurements must be performed before the start of the storage stage. This information can be used for public acceptance and trust during the subsequent storage stage, especially due to the cyclicity.
2. Before starting the cyclic storage of hydrogen of the (pilot) project, it is important to perform required geophysical and petrophysical surveys to obtain images of the subsurface structures with sufficient resolution. Given the challenges with imaging in and below salt formations,

fibre optics in the well, may provide a solution to improve measurements. These images will serve as baseline information against which later surveys could be checked for detection and characterization of changes in the subsurface, i.e., for time-lapse monitoring. Just like for storage in depleted gas reservoirs, baseline measurements of the local seismicity are needed before the starting of the project. Monitoring of microseismicity might help to timely identify cavern instability. Monitoring of hydrogen migration through the overburden (above the salt) layers during the cyclic storage may be hampered by the fact that hydrogen probably reacts with sediments and fluids.

3. Using geophysical methods with measurements at the surface or in wells would allow obtaining high-resolution images of the shallower and deeper subsurface. For example, the seismic reflection method with active sources has shown its capability of accurate monitoring of changes in the reservoirs and/or caprock [180, 181], but also of accurate imaging of salt structures and faults. Furthermore, obtaining accurate seismic-velocity and quality-factor information allows continuous high-resolution temporal and spatial localization of induced seismicity, accurate moment-tensor inversion, and timely decision-making to prevent subsidence. The induced-seismicity data comes from continuous passive seismic recordings. These recordings could also be used for turning parts of the passive data into virtual seismic-reflection data [182] for imaging of the subsurface structures at different time intervals, and thus monitoring of changes at costs lower than using active source but possibly at lower resolution. Local stress changes in the rocks lead to significant changes in the seismic velocities, which can be monitored using seismic methods. Changes in the reservoir fluids, or in fault zones, lead to changes in the electric resistivity, which can be monitored using electromagnetic methods. In this sense it is also important to investigate whether reservoir saturation tools and nuclear magnetic resonance tools (typically used to measure movements in gas – water contacts in gas reservoirs) are affected by the presence of hydrogen in reservoir fluids. Joint seismic and electromagnetic data inversion can better inform about such changes.

While most of the above-mentioned methods have proven their usefulness for monitoring of hydrocarbons exploitation and storage, and of CO<sub>2</sub> storage, they have not been tested for monitoring of hydrogen storage with its specific and partially unknown characteristics during long-term storage and production cycles. It is thus important that seismic field tests with active and passive sources are performed at project sites to understand the sensitivity and resolution of the methods. Similarly, the development of capacitive electrodes can make it possible to develop an electromagnetic monitoring system with the ability to perform stable time-lapse measurements over decades.

A workflow for monitoring the integrity of the caprock, reservoir, and the wellhead should have 2D or 3D seismic measurements at the surface and/or wells from active seismic sources. Between different seismic acquisition campaigns with active sources, passive data should be collected continuously for monitoring for induced seismicity, but also for producing virtual seismic data for monitoring. When borehole electrodes are available and can be used, time-lapse transient electromagnetic data should be collected with source on the surface and electrodes in a borehole. Where possible, borehole electrodes can be used as current electrodes, serving as a source of electromagnetic fields. With in-well measurements, a better definition of resistivity changes is possible than with surface-to-borehole measurements.

### 3.5 Impacts on development and operations

Table 3-1 summarizes various hazards and adverse effects that relate to different aspects of storage integrity in both a porous rock and salt cavern storage setting. For each hazard or effect possible causes are summarized. The last two columns hold a summary of the current state of art knowledge and recommended key actions needed to improve our understanding and reduce uncertainties in a



safe development and operation of UHS. A generic overview of potential hazards and adverse effects is included in Table A-1 in Appendix A.

Table 3-1: Overview of current understanding of potential UHS-related impacts on storage integrity in porous reservoirs (A) and salt caverns (B).

A: Hydrogen storage in porous rock formations (sedimentary systems).

Potential hazard / adverse effect	Possible causes	Processes and characteristics	State of knowledge	Required actions and knowledge
Leakage	Degrading sealing capacity of caprock	Sub-grain scale/ intergranular processes, e.g., mineral dissolution/precipitation, crack growth, hydrogen sorption	Laboratory experiments and modelling work conclude that shale caprocks can act as an effective seal for hydrogen due to low reactivity with hydrogen. The impact of sorption still requires research.	Quantitative experimental work remains to be carried out to further expand and confirm understanding of potential impacts of geochemical reactions and sorption.
	Diffusion and permeation through caprock	Upward dispersion of hydrogen through the caprock, possibly amplified by H <sub>2</sub> -driven geochemical reactions and mineral dissolution/precipitation in caprock	Laboratory experiments and modelling work show insignificant diffusion losses of hydrogen through caprocks (high capillary entry pressure).	Breakthrough pressures of hydrogen in shale caprocks needs to be measured experimentally and under realistic subsurface conditions.
	Migration through fractures	Sub-grain scale/ intergranular processes, e.g., mineral dissolution/precipitation, crack growth, hydrogen sorption impacting mechanical and transport properties of the seal.	Leakage through fractured clay-rich rock is still poorly quantified.	Experimentation and monitoring of hydrogen migration through fractured caprock in a real subsurface environment
Induced seismicity	Fault slip and fracture development/ propagation	Rock deformation and lower threshold for fault slip due to fast-cyclic loading and high-pressure variation	Few experimental data on the impact of H <sub>2</sub> on reservoir rock mechanics and stability/ integrity. Most knowledge on cyclic stress-regime impacts comes from UGS projects	Further quantitative experimental work on different rock types and reservoir conditions to increase understanding of cyclic loading impacts on reservoir stability and fracture generation and propagation in the presence of H <sub>2</sub>
		Mineral precipitation and dissolution in carbonate, sulphate, sulphide, and ferric-bearing reservoir rocks, subcritical crack growth due to weakening molecular bonds		
		Progressive fatigue of reservoir rock due to intergranular clay swelling/shrinkage cycles		
		Increasing slip-tendency due to geochemical alteration in presence of hydrogen		
Subsidence	Pressure and temperature cycling could lead to reservoir fatigue and/or permanent compaction.	Sub-grain scale/ intergranular processes, e.g., mineral dissolution/precipitation, crack growth, hydrogen sorption impacting mechanical properties of the reservoir.	Laboratory studies on the effect of pressure and temperature cycling under realistic in-situ conditions are still sparse.	Quantitative experiment work is needed to investigate the impact of cycling frequency and magnitude on reservoir integrity.

## B: Hydrogen storage in salt caverns (evaporitic deposition)

Potential hazard / adverse effect	Possible causes	Processes and characteristics	State of knowledge	Required actions and knowledge
Leakage	Damage zone permeation	Cyclic changes in cavern pressure (frequency, magnitude) may lead to progressive hydrogen penetration into the surrounding damage zone. Damage zone increase due to overpressurisation caused by trapped hydrogen.	Laboratory experiments and experiences from existing natural gas and compressed air storages.	Further experience must be gained from cavern storage projects with pure hydrogen (influence of compressibility and temperature effects of hydrogen as well as different cyclic loading cycles).
	Shear or hydraulic fracturing at cavern roof	Overpressurisation in brine-filled caverns due to increasing temperature of brine (expansion) and simultaneous cavern convergence due to salt creep.	Laboratory experiments and experiences from existing natural gas and compressed air storages.	Further experience must be gained from cavern storage projects with pure hydrogen (influence of compressibility and temperature effects of hydrogen as well as different cyclic loading cycles).
	Cavern overburden & underburden communication	Extensive permeation into the salt surrounding the cavern, or leakage pathways resulting from hydraulic or shear fracturing.	An extensive knowledge base exists for brine-cavern processes during operation and after cavern closure and shut-in.	Cavern design and operations should consider the rock-mechanical behaviour of a cavern (including pressure build-up) over the entire life cycle comprising post abandonment phases.
Subsidence	Salt creep	With increasing depth and temperature the visco-plastic behaviour of salt changes. Salt cavern walls will slowly move inwards if cavern pressure does not balance the lithostatic pressure. Small deviatoric stresses in the farther field, away from the cavern wall, may lead to increased creep and associated surface subsidence.	New insights are being developed on long term salt creep behaviour under low-deviatoric stress conditions, further away from the cavern wall.	Cavern design and operations should consider the rock-mechanical behaviour of a cavern (including pressure build-up) over the entire life cycle comprising post abandonment phases.
Induced seismicity	Fault reactivation	Salt creep below brittle overburden rock could lead to movement along pre-existing faults.	New insights are being developed on long term salt creep behaviour under low-deviatoric stress conditions, further away from the cavern wall.	Cavern design and operations should consider the rock-mechanical behaviour of a cavern (including pressure build-up) over the entire life cycle comprising post abandonment phases.

### 3.6 Summary of findings and recommendations

Storage in underground porous media and salt caverns is not a new concept and has been widely applied at commercial scale for UGS and CC(U)S. Despite the unique chemical and physical properties of hydrogen, the knowledge, skills, and experiences obtained from UGS and underground storage of CO<sub>2</sub> remain relevant. There are ample fundamental research questions surrounding safe hydrogen storage. Addressing those questions and assessing the operational constraints to ensure both long-term safety and economic efficiency, should be done. This concerns the following main areas of research with regards to the integrity of the underground storage reservoir and seal.

#### **Minimizing hydrogen losses via the caprock and seal of porous reservoirs**

Laboratory experiments and modelling work conclude that shale caprocks can act as effective seal for hydrogen due to low reactivity with hydrogen while insignificant diffusion and dispersion losses of hydrogen through caprocks is expected due to the high capillary entry pressure. Leakage through fractured clay-rich rock is still poorly quantified.

Following key actions are required to improve and confirm the understanding of potential hydrogen losses via the cap rock:

- Quantitative experimental work to assess and confirm potential impacts of geochemical reactions on caprock integrity and the effective diffusion and dispersion coefficient of hydrogen in shaley caprock.
- Experimental measurement of breakthrough pressures of hydrogen in shale caprocks under realistic subsurface conditions.
- Monitoring of potential migration of hydrogen through fractures in laboratory experiments and real subsurface environments.

#### **Maintaining mechanical integrity of salt caverns under high-frequency loading and unloading with hydrogen**

There are ample experiences from laboratory experiments and from existing natural gas storages and compressed air storage on permeation of gases into the cavern wall damage zone and on potential shear or hydraulic fracturing at cavern roof. An extensive knowledge base exists for brine – cavern processes during operation and after cavern closure and shut-in. Novel insights are being developed on long term salt creep behaviour under low-deviatoric stress conditions, further away from the cavern wall.

With regards to the integrity of hydrogen containment and stability of salt caverns further experience must be gained from cavern storage projects on:

- Permeation and progressive penetration of hydrogen into the damage zone and how this is influenced by compressibility and temperature effects of pure hydrogen, fast-cyclic changes in cavern pressure and potential trapping of hydrogen in the damage zone.
- Influence of cavern design and operations on the rock-mechanical behaviour of a cavern (including pressure build-up) over the entire life cycle comprising post abandonment phases.
- Effects of salt creep below brittle overburden rock formation on potential movement along pre-existing faults.

#### **Predicting fracture network formation and minimize risk of fault slip during cyclic hydrogen loading and unloading in porous reservoirs**

Most knowledge on cyclic stress-regime impacts on fracturing and fault slip comes from UGS projects. There is limited experimental data on impact of H<sub>2</sub> on reservoir rock mechanics as well as the impacts of fast cyclic loading and unloading with rapidly alternating high pressure variations which are typical to UHS operations.

Further quantitative experimental work is needed on different rock types and realistic reservoir conditions to increase understanding of:

- Cyclic loading impacts on reservoir stability and fracture generation and propagation in the presence of hydrogen.
- Effects of mineral precipitation and dissolution and weakening molecular bonds on subcritical crack growth.
- Progressive fatigue of reservoir rock due to intergranular clay swelling/shrinkage cycles.
- Increasing slip-tendency due to geochemical alteration of the fault zone in presence of hydrogen.

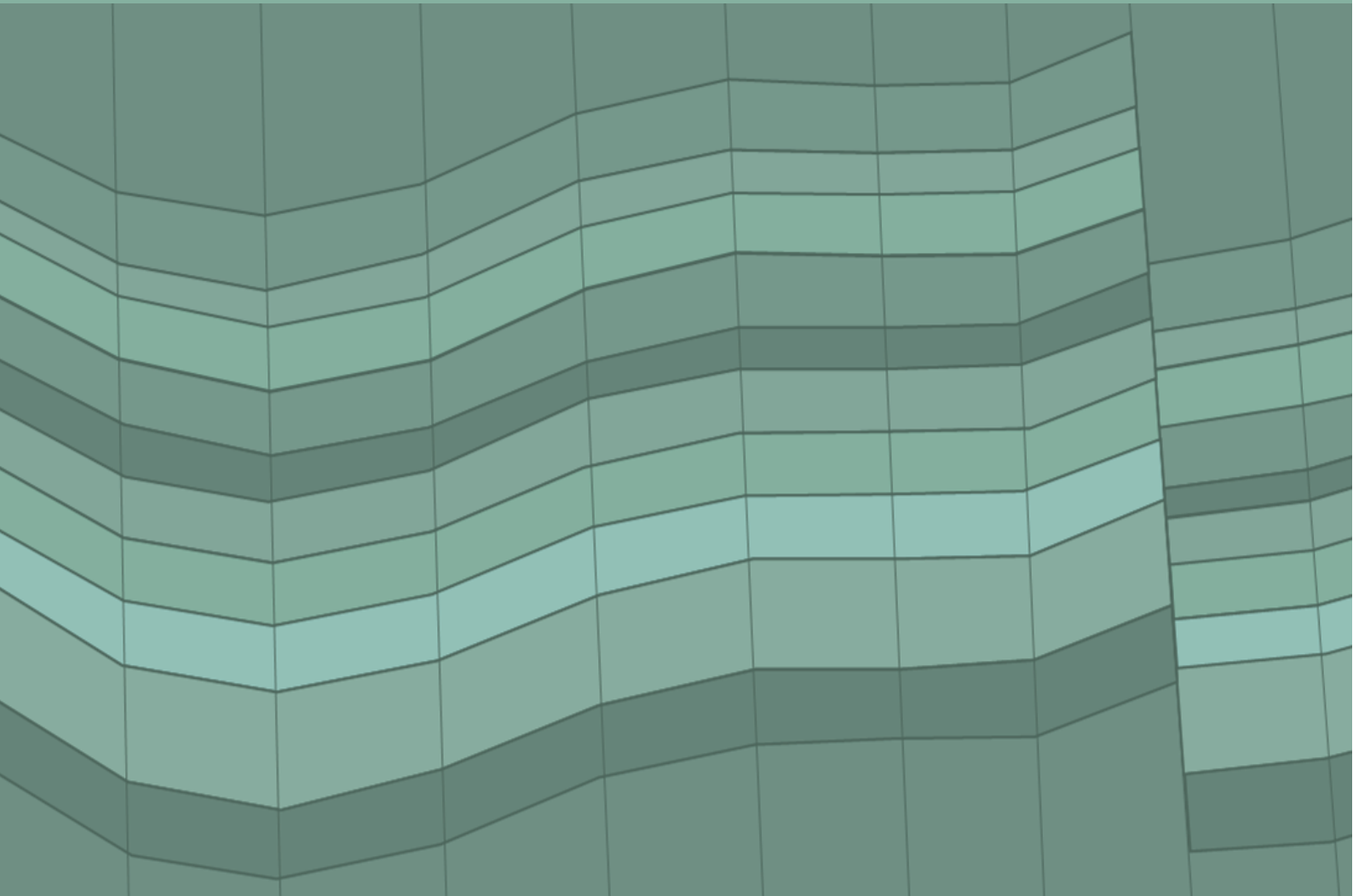
### **Monitoring integrity of caprock, seal, reservoir and faults**

There is extensive experience with the use of various geophysical and geological measurement and monitoring methods from existing hydrocarbons exploitation, underground gas storage and CO<sub>2</sub> storage yet the experiences with UHS are mostly lacking or immature.

There is a need to further develop and test methods for monitoring of caprock and reservoir integrity issues in the case of underground hydrogen storage. Specific emphasis should be put on the spatial and timelapse resolution as well as the sensitivity of monitoring instruments. Monitoring data should be integrated with numerical models to validate reservoir processes at field scale.

# CHAPTER 4

## Storage Performance



Hydrogen physics and thermodynamics relevant to storage in salt caverns

Hydrogen flow and recovery in porous rock and salt caverns

Cushion gas effects

Impacts on development and operations

## 4 Storage performance

### 4.1 General Introduction

The economic viability of any underground hydrogen storage project and its ability to fulfil a given storage demand profile of end-users is largely determined by the site-specific reservoir performance characteristics. The demand profile typically determines the expected maximum production rate (load) and the required duration of withdrawal at a given production rate (load duration). The operational performance parameters typically comprise injection/production rates, accessible working gas volume, required cushion gas volume, recoverability and quality of hydrogen withdrawn from the reservoir, and reservoir, and load duration. These parameters depend on the interplay between the site-specific geological reservoir characteristics and the design and engineering principles used to drill and complete the wells (e.g., diameter, tubing, perforation) and construct the surface storage facility components (such as compressors).

This chapter focuses on the variables, criteria and approaches used to determine performance of storage operations through evaluation and modelling of relevant reservoir characteristics. The outcomes underpin the criteria and methods used to select, rank and validate potential storage sites (Chapter 5) and to design the wells and storage facilities (Chapter 6). Various other aspects may relate to performance as well, such as containment and consequences for abandonment strategies. These topics are addressed in Chapter 3 and 6 respectively. In this chapter, the available knowledge has been collated to assess the following main performance aspects:

- Potential load profiles which define the expected volumes, rates and cycling frequencies to be delivered by the underground storage site and which depend on the demand profile (i.e., peak shaver, long-term buffering or strategic reserves).
- Storage volume, which is the total volume of gas (in this case pure hydrogen or hydrogen-natural gas blends) that can be contained at the maximum working pressure. The total storage volume consists of i) the working gas volume and ii) the cushion gas volume.
- Working gas representing the dynamic volume of gas effectively contributing to the injection and withdrawal operations.
- Cushion gas representing the static volume of gas/liquid that remains in the reservoir for the entire operational lifetime of the storage facility to sustain a minimum reservoir pressure required for storage operations. This gas/liquid may need to be injected prior to the start of storage operations in case of a salt cavern or a gas field that was depleted below the minimum pressure. There are different requirements and implications of using different types and volumes of cushion gas on the effectiveness of storage operations and economics.
- Storage facility that may be operated with variable and constant (plateau) rates for injection and withdrawal of hydrogen, which can be estimated or simulated based on existing analogue, analytical and numerical models. Thereby the actual pressure will vary between the maximum and minimum allowable reservoir pressure.
- Experimental and modelling results of hydrogen flow behaviour at the pore and Darcy scale under varying conditions, which is needed to identify the primary influencing performance parameters and processes such as mixing and diffusion (e.g., imaging and 4D monitoring of hydrogen flow through porous reservoir rocks and diffusion through seals including the host salt for cavern storage).
- Potential interactions between the reservoir/well and surface (treatment) facilities, linking through to the remit of Chapter 6.
- Potential impact of microbial activity and geochemical reactions (Chapter 2) and geomechanics aspects including reservoir/seal integrity (Chapter 3) on performance (Figure 4-1).



Salt/rock caverns and porous rock formations have very different performance characteristics such as the type of pore space as well as differences in physics, thermodynamics and chemical properties and compositions of rock matrix and in-situ fluids. Nevertheless, there are several considerations specific to hydrogen that are relevant to storage in both porous formations and salt caverns [67, 90, 132, 176, 183], which are summarised below:

- Physical and chemical properties of hydrogen differ from other fluids that may be stored in the subsurface (e.g.,  $\text{CH}_4$ ,  $\text{CO}_2$ ).
- Reactivity of hydrogen may cause geochemical reactions with interstitial fluids and host rocks.
- Hydrogen may stimulate growth of microbes leading to consumption (loss) of hydrogen, degradation of the hydrogen quality and even reduction of the reservoir permeability in porous rocks (see Chapter 2).
- Repeated injection cycles, or storage at different pressure ranges may alter the natural subsurface stress state and cause mechanical damage specially at the wellbore or trigger sensitively-stressed faults.
- Physical properties and consequently the storage performance can be altered due to hysteresis effects.
- Changes in the subsurface stress state in deeper halite accumulations that host solution-mined caverns can lead to creep, changes in cavern morphology and a reduction in storage capacity.

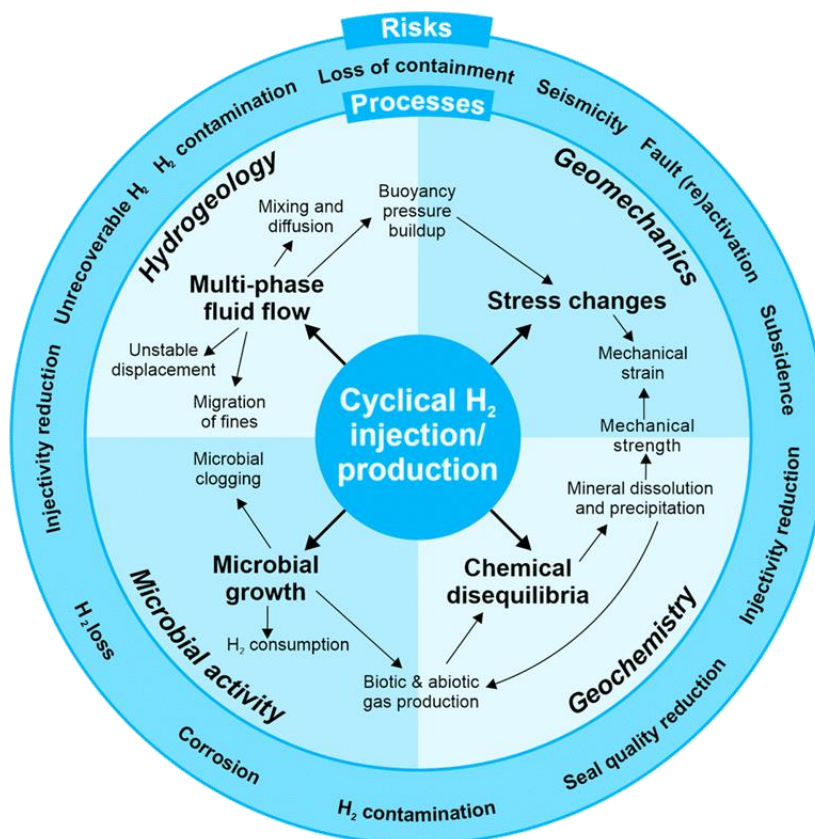


Figure 4-1: Range of considerations, risks and processes relevant to understanding storage performance in both solution-mined caverns and porous rocks. Source: [90].

## 4.2 Experiences

### 4.2.1 *Underground natural gas storage and compressed air energy storage*

The many existing operational underground natural gas storage facilities (UGS) in porous reservoirs and salt caverns [184], provide valuable analogues to assess storage performance and model dynamic behaviour of hydrogen and other gases. The main difference will be the requirement of higher withdrawal/injection rates and cyclicity to match fluctuating demands. The effects of this operational demand in the storage unit (integrity of a cavern or porous rock) still need further investigation (e.g., [185]). Similarly, the experiences from Compressed Air Energy Storage sites (CAES) in salt caverns may also be relevant for underground storage of hydrogen (e.g., [186, 187]). When using such of analogue experiences it is important to account for the different physical and chemical characteristics of hydrogen compared to natural gas, as well as the different requirements with respect to withdrawal/injection rates and cyclicity of storage operations.

### 4.2.2 *Pure hydrogen storage in salt caverns and lined rock caverns*

Existing commercially operated underground storage sites for pure hydrogen are currently limited to salt caverns (Table B-2, Appendix B). These offer a scalable option for underground storage of hydrogen where sufficient halite or rocks suitable for lined-cavern development exists. The geological setting, design and operation of these caverns are mostly similar to caverns that are operated for natural gas storage. The modelling and determination of hydrogen storage performance in caverns is generally quite straightforward and not complicated by varying matrix porosity/permeability and hydrodynamic processes that are characteristic for porous rock storage. A storage volume in a salt cavern-operated facility is scalable by the number of caverns that can be realized within the structural limitations of the salt structure.

### 4.2.3 *Storage of hydrogen in porous rock formations*

The concept of the ‘hydrogen storage play’ [188] defines the storage in porous rocks as a system consisting of a reservoir, seal and trap. This is similar to some of the main elements of natural hydrocarbon accumulation in petroleum plays (excluding the requirement for a source rock at depth) or to CO<sub>2</sub> underground storage in porous rocks. This mainly concerns depleted gas fields but may also be relevant to oil reservoirs with gas caps, deep saline aquifers and coal seams, [189, 190]. The current lack of operational porous storage facilities results in considerable uncertainty regarding the potential load profiles, cyclic load schemes, flow behaviour and issues concerning cushion gas. Consequently, there remains considerable uncertainty about the efficiency and feasibility UHS in porous rocks [148].

## 4.3 Hydrogen physics and thermodynamics relevant to storage in caverns

The thermodynamics of hydrogen in solution-mined caverns is reviewed in the literature [20, 191]. For hydrogen, the Joule–Thomson coefficient is negative at certain conditions, resulting in a temperature increase during isenthalpic throttling (i.e., cavern filling), but isenthalpic conditions are not experienced during cavern emptying. This results in a smaller temperature variation in the cavern than experienced during similar cycling of stored natural gas. Additionally, the compressibility factor for hydrogen is greater than that of methane, resulting in a smaller working and cushion gas volume than experienced with natural gas storage in caverns.

The variation in temperature and pressure within a storage cavern volume and its walls due to heat conduction can lead to thermal convection, salt cavern deformation through creep or (micro)fracturing and ultimately influence injection and withdrawal rates. Note that there exist differences in composition of cavern walls between halite, anhydrite, mudstone and other insoluble material.

Based on the literature [178, 192] the requirements for calculating cavern storage capacities are summarised below.

**Geothermal gradient:** This gradient results in an increase in bedrock temperature with depth and is assumed to heat a cavern to equivalent temperatures. This can result in a temperature variation of 3 – 7.5 °C between the top and base of a cavern, depending on the height (small or large) of the caverns. This will influence gas volume in the cavern.

**Overburden pressures:** Pressure is a controlling factor on gas volume and mass that can be stored in a void. This is a function of depth, which controls the overburden pressure. Storage pressures are normally limited to between 20 – 80% of lithostatic pressure in order to maintain geomechanical stability of a storage cavern. To maintain the rock salt material stability and operate long-lived caverns, the primary depth target for UHS salt caverns is considered to be between 1,000-1,500 m [176, 193]. Low pressures may enhance creep, as a salt cavern in the Eminence salt dome, in Mississippi, has experienced a volume decreased of more than 40% when operated at low pressures [194]. It is suggested that layers of anhydrite in bedded halite formations may result in a reduced strength of the halite unit, which could be exacerbated by cycling pressures during cavern operation [195] (e.g., especially of cycles at a greater rate than seasonal were considered). This is due to the formation of micro-cracks at the halite – anhydrite interface that could enable creep and may be more relevant for hydrogen storage than natural gas due to the smaller molecule size of hydrogen.

**Column height conversion factor:** This factor describes the ratio of the pre-production natural gas column height to the hydrogen column height. For hydrogen, this ratio is greater than 1, meaning that hydrogen can be stored at greater pressures than methane, although original reservoir pressures should be carefully managed to ensure reservoir and seal integrity and performance are maintained [37]. Repeated injection and withdrawal cycles have the potential to alter the geomechanical integrity of the caprock and could contribute to seal failure.

**Compressibility factor:** Upper and lower limits for gas operating pressure (derived from underground gas storage sites) inform density calculations at a particular pressure.

**Mass of working gas:** This mass is influenced by the pressure of the stored gas, volume of cavern and a safety factor. The safety factor accounts for lost volume due to insoluble material in the cavern sump, brine remaining in the cavern and irregularities in cavern shape, together assumed to be ca. 70%.

**Energy storage capacity of a cavern:** This capacity is given by the lower heating value and mass of working gas.

**Geochemical reactions:** As mentioned in Chapter 2, it is expected that hydrogen will react with certain naturally occurring rock minerals and fluids, depending on temperature conditions in the reservoir. Moreover, hydrogen can dissolve in pore fluids and residual hydrocarbons.

#### 4.4 Hydrogen flow in salt cavern and porous rock storage

Multiple fluid properties and physical processes are relevant to the understanding of hydrogen flow behaviour in the subsurface. These include compressibility, density and viscosity, amongst others, and the physical processes: diffusion, dispersion, dissolution, advection, adsorption/desorption, mobility ratio, capillary pressure, wettability, compression and mixing between hydrogen and interstitial pore fluids [196]. These properties and processes are influenced by changes in temperature, pressure, and presence of other fluids such as water, and thus the relationship between these critical aspects and the operation and location of an underground storage site are relevant to understanding storage efficiency. Reservoir properties should also be considered as changes in (effective) porosity and (relative) permeability (including changes due to wellbore mechanical damage, rock deformation,

formation clogging due to microbial or geochemical reactions), which can also affect reservoir efficiency, productivity and performance.

The knowledge of gas behaviour in the subsurface is derived largely from studies considering nitrogen and methane, both of which are significantly heavier gases with larger molecule sizes, and it is unclear whether these can be used to inform the behaviour of hydrogen in underground storage [112, 197]. Some studies indicate that nitrogen may be suitable for use as a proxy for hydrogen in multi-phase fluid experiments, although hydrogen has a lower viscosity, higher mobility and greater density difference with water than natural gas/CO<sub>2</sub>, which will affect hydrogen behaviour in the subsurface [198]. Under the influence of capillary and gravitational forces, e.g., when the hydrogen plume reaches the top of the reservoir, it is shown that hydrogen and methane have the same wettability characteristics [199]. Also, from the surface force analyses, ignoring bio-geochemical reactivities, the wetting properties of a rock surface can hardly be affected by gases such as methane, hydrogen and nitrogen [200]. In presence of bio-geochemical reactivities, further research is needed to characterize the wettability of the rock in presence of hydrogen and living organisms. Molecular dynamics studies are important to characterise the wettability, dissolution and equation-of-state of hydrogen and its mixtures over a wide pressure and temperature ranges [201]. It is also acknowledged that there are few studies of hydrogen flow in the subsurface, resulting in a poor understanding of multi-phase flow of hydrogen in the subsurface [202]. Recently the cyclic transport of hydrogen in porous rocks has been successfully visualized under CT scan in the laboratory environment for pressures up to 100 bar [203, 204, 205]. These indicate the upscaled transport functions (such as relative permeabilities and capillary functions) needed for reservoir simulations. In addition to the factor effecting the flow performance, the much lower calorific value of hydrogen (10.8 MJ/m<sup>3</sup>), relative to, e.g., natural gas (ca. 39 MJ/m<sup>3</sup>), has also significant implications on the ultimate flow performance in terms of energy [197]. This, together with the lower density (eight times) and compressibility (0.8 – 0.9), also implies that more space will be required for hydrogen to store the same amount of energy.

#### 4.4.1 *Hydrogen flow relevant to salt cavern storage*

The maximum injection and production rates in solution-mined caverns are limited by the temperature and pressure changes that wells transporting gas to a cavern can handle. For many operational natural gas storage caverns, this broadly equates to a daily stress change of ca. 0.8 MPa [192]. Variations in the injection and production rate will also affect downhole temperature changes associated with hydrogen expansion, and the combined thermodynamic effect will have its impact on safe storage limits.

#### 4.4.2 *Hydrogen flow relevant to porous rock storage*

The behaviour of hydrogen in porous rocks is influenced by the physical properties of hydrogen, and the temperature, pressure and heterogeneity of the storage unit. Any chemical changes that happen in-situ and the pressure differential between the wellhead pressure and bottomhole pressure are also considerations. As stated before, further research is required to characterise how the hydrogen-brine-host rock bio-geochemical reactions can alter hydrogen transport behaviour. Hydrogen dispersion may also influence its transport in porous rocks (see Chapter 3 for full discussion).

Important input parameters to flow models of hydrogen include detail on how hydrogen influences interactions of rock and fluids within the reservoir, including transport properties such as relative permeability, capillary pressure, and mixing in porous media (see Chapter 2 for full discussion). These influence the amount of lost or retained hydrogen in the formation (affecting the economic viability of storage). Data from multiple storage scenarios is required to understand propagation and distribution of hydrogen saturation development throughout the porous reservoir and recoverability of hydrogen.

During injection, hydrogen will displace as well as mix with formation fluids, resulting in complex displacement patterns influenced by the natural fluid and rock properties [90]. Laboratory experiments can be used to characterise flow/transport properties (e.g., hydrogen/water multi-phase flow at core scale). Work found in [203] indicates that gravitational, viscous and capillary forces are relevant considerations when understanding hydrogen flow through porous rocks, and that the behaviour and distribution of hydrogen is influenced by processes including gravitational segregation, fingering and channel formation and hydrogen spreading in response to variations in lithological properties. Primary drainage, imbibition and secondary drainage relative permeabilities can also inform understanding of field-scale flow modelling and injection and withdrawal strategies [206]. Fingering may be more pronounced when hydrogen injection rates increase [207]. Prediction of these complex transport processes will ultimately contribute to effective reservoir management. The multi-phase properties of hydrogen in porous rocks remains a significant knowledge gap. There are uncertainties regarding hydrogen (and its mixtures) behaviour at in-situ thermodynamics conditions (specially pressure and temperature). It could be assumed that its low density may result in the gas collecting directly beneath caprocks [90]. However, gravitational segregation may be a subordinate force to diffusion in most circumstances [208]. Bespoke viscosity equations may be required to describe the behaviour of hydrogen in the subsurface [209].

The behaviour of hydrogen in porous rocks has several important knowledge gaps, including the flow behaviour and recoverability. These can be described by relative permeability curves that model multi-phase flow through sandstone [198] or the directly measured curves by core-flood experiments [203]. Their study indicated that the pore structure and porosity have the greatest effect on relative permeability of hydrogen, with increasing pressure reducing relative hydrogen permeability. An increase in salinity resulted in a decrease in relative hydrogen permeability, possibly due to formation drying near the injection zone.

### 4.5 Hydrogen recovery in salt cavern and porous rock storage

Multiple processes can trap hydrogen in the subsurface. Hydrogen has the potential to dissolve in formation fluids or residual fluids remaining in caverns. Other processes, mostly relevant to storage in porous rocks, include residual trapping, edge effects, consumption by microbial populations, reactions with host rock minerals and potential leakage. For many of the parameters of interest, the response could vary and evolve over time and between different reservoirs or storage projects. This is due to local conditions and projects with different or variable offtake/injection cycles. These uncertainties result in the topic of hydrogen recovery remaining a focus of further study.

#### 4.5.1 Hydrogen recovery relevant to salt cavern storage

It is assumed that cushion gasses in caverns would be the same as the working gas in storage caverns. The solubility of hydrogen in formation fluids is relevant as it can result in a loss of recoverable hydrogen gas from the storage complex. Hydrogen is less soluble in brine than in fresh water. In solution-mined caverns, brine remains in the cavern and there is the potential for hydrogen to dissolve into these brines. There is a general lack of data concerning hydrogen solubility in saturated brines [20]. The solubility of different gases in saturated brines is recently investigated in various studies [201, 210, 211, 212]. Hydrogen dissolution into brine can potentially limit the working gas volume by a few percentage, if the cavern is not fully de-brined [20].

#### 4.5.2 Hydrogen recovery relevant to porous rock storage

Hydrogen has a low viscosity and high mobility; this may result in faster injection and draining but also results in hydrogen being less effective in displacing brine from the reservoir [90]. This may result in the development of isolated pockets of hydrogen in the storage complex that become stranded (i.e.,



unrecoverable). This is likely more relevant for depleted oil reservoirs and saline aquifers, less so for depleted gas reservoirs where gas – gas displacement is important, leading to potentially higher impurities in hydrogen but without loss of stored product.

### **Dissolution and diffusion**

Residual gas saturation in pore-fluids may be a relevant consideration in both depleted reservoirs and/or saline aquifers as this will influence how much of the stored product may remain trapped in the formation. A study based on models in the Rough porous storage reservoir offshore UK indicated that combined hydrogen losses from dissolution and diffusion could be reduced to less than 0.1% of the total hydrogen stored [183]. An element of mixing would be expected between any residual hydrocarbons in depleted reservoirs (such as Rough) and stored hydrogen; and that for the first few cycles of injection and hydrogen withdrawal, some of these hydrocarbons would be extracted along with the hydrogen, albeit decreasing with reported cycles [183], until equilibrium has been reached. The degree of mixing also depends on the reservoir heterogeneity, flow rates, and the in-situ and cushion gases.

### **Residual trapping**

There is the potential for small bubbles of hydrogen to remain trapped in pores that cannot be recovered; this process is known as ‘residual trapping’ and could account for some minor losses of hydrogen, thought to be a process most relevant in the first injection/extraction cycle [188]. During subsequent storage cycles, losses to residual trapping are expected to be much less of a concern as effective pore spaces will be saturated with hydrogen [202].

### **Microbial stimulation**

This aspect is fully discussed in Chapter 2. There is potential for hydrogen to stimulate the growth of microbial populations, which may consume hydrogen and/or have the potential to generate hydrogen sulphide ( $H_2S$ ) which may require post-extraction processing of the stored product (see Section 4.3) and require accommodation via engineering solutions due to exposure to  $H_2S$ . Also, the biogeochemical reactions, as stated before, can alter hydrogen transport properties. This requires further research.

### **Potential leakage**

Integrity of storage units is discussed in detail in Chapter 3. Integrity of storage units is discussed in detail in Chapter 3. There is a lack of data describing breakthrough pressures of hydrogen in caprocks. Hydrogen buoyancy is high, meaning even moderate columns of hydrogen could exhibit very high buoyancy pressures, which can breach caprocks in certain settings [90]. Cyclic stresses in response to repeated injection and production alters the state-of-the-stress of the storage unit [132]. These could lead to reservoir compaction, porosity reduction, reduced permeability, subsidence/uplift and/or fault reactivation/induced seismicity. It can also impact well integrity, including cement and casing, beyond the storage unit, and generate fractures in caprocks. Operational techniques, such as reducing lateral spreading of hydrogen [90], and proper site selection can significantly help with limiting the risk of leakage and maximizing the recovery factors.

### **Geochemical reactions**

The potential for geochemical reactions is discussed in detail in Chapter 2. Geochemical reactions, if these occur, could lead to the dissolution or precipitation of cements and thus the permanent deformation of the reservoir [90]. These could also affect the stress state of faults. The reservoir may be further degraded by sorption of hydrogen to clay minerals (see Section 2.2).

## **4.6 Cushion gas effects**

The role of cushion gas in underground storage sites is to maintain storage pressures, ensuring a minimum pressure to maintain geomechanical integrity of a storage void. In solution-mined caverns for example, it limits creep closure and avoids tensile failure of the cavern walls or roof. In porous rock



storage, cushion gas provides the reservoir pressure for sufficient outflow performance and also prevents the ingress of formation fluids into the working storage zone. Insufficient reservoir pressures lead to poor flow rates or no flow at all. There is a minimum reservoir pressure which determines the operating limit of the storage facility during production/withdrawal mode. This reservoir pressure may be set by the natural hydraulics or any compression facilities at the surface, depending on the operating mode and system set-up. In cavern storage sites minimum pressure is also related to outflow, as well as for geomechanical reasons the cavern pressure is kept above a threshold value in order to limit cavern convergence (and consequently subsidence). Storage facilities at greater depths/pressures will require a greater volume of cushion gas than storage facilities at shallower depths/lower pressures. Cavern design is required to find the optimum technical and economic range between storage and cushion gas volumes.

It is common for working gas and cushion gas to be of the same composition [90, 188] although alternate cushion gas compositions and/or carrier gases required for compression ( $\text{CH}_4$ ,  $\text{N}_2$ ,  $\text{CO}_2$ ) have been discussed by several authors. Different compositions of cushion gases may be more appropriate for depleted gas/oil reservoirs or saline aquifers. Alternative cushion gases would have the potential to:

- reduce costs,
- reduce the carbon footprint,
- reduce the density contrast between hydrogen and formation waters, and
- increase costs due to the requirement for reservoir management/post-storage processing and refining of hydrogen.

### 4.6.1 *Cushion gas effects relevant to cavern storage*

Cushion gas requirements are influenced by the maximum and minimum cavern operating pressures; for operational natural gas storage caverns, cushion gas requirements are typically in the region of 40% of the total volume of the cavern (e.g., a ratio of 40/60% cushion gas vs. working gas) [192].

For caverns operating at greater depths/temperatures, halite may become naturally ductile as the plastic limit of halite is exceeded, operation by brine compensated mode/steady pressures (isobaric) results in working gas being retrieved by the injection of brine to the cavern. For caverns operated by changes in pressure, cushion gases could be retrieved by re-brining of the cavern.

### 4.6.2 *Cushion gas effects relevant to porous rock storage*

In [148] it is indicated that residual natural gas in depleted gas fields may be a positive factor as it could contribute to the required volume of cushion gas necessary for storage performance.

For porous rock storage, cushion gas requirements are variable, dependent on local geological conditions, temperature and overburden pressures, and figures between 33 – 66% of working gas have been suggested [207, 213]. At the higher proportions, the amounts of cushion gas may represent a barrier to development considering the relatively high capital costs of cushion gas. The proportion of cushion gas required in a depleted gas reservoir may be less than that required in a saline aquifer as residual natural gas may contribute to the volume of cushion gas required, with estimates of cushion gas required in aquifers being as high as 80% of reservoir capacity [214]. In [178] it is reported that cushion gas requirements of aquifers may be larger than those for depleted oil and gas reservoirs, and that “gas leakage is inevitable”.

Mixing of hydrogen with other fluids present in the reservoir (hydrocarbons or non-hydrogen cushion gases) will happen, affecting the quality of the stored product, although there is a limited dataset to allow a full understanding of the impacts of this aspect (see Chapter 2). Some projects consider injecting mixtures of hydrogen with natural gas (‘hythane’), which may also impact the transport and

phase properties of UHS [215]. Further research is needed to investigate the impacts of different hydrogen – natural gas mixtures on storage performance (e.g., thermodynamics and fluid dynamics). Ultimately these insights are needed to find optimum mixtures for specific storage scenarios and demand profiles.

Costs of cushion gas could be reduced by employing an alternative gas (e.g., carbon dioxide, methane, nitrogen), although these may result in the mixing and contamination of stored hydrogen, necessitating post-extraction processing where this is the case [216]. The use of alternative cushion gases may result in altered thermophysical properties of hydrogen that may need to be considered to maintain operational efficiency; this may also affect the flow pattern of the hydrogen mix in the storage unit.

#### 4.7 Impacts on development and operations

In Table 4-1, Table 4-2 and Table 4-3 an attempt has been made to describe risks in terms of most important first, becoming less important down each table. Impacts on storage volume are considered most important, followed by impacts on flow performance, then reactions involving hydrogen that could lead to technical issues. Impacts that affect cushion gas volumes (i.e., more economic risks) are considered least important in the context of storage performance. A generic overview of potential hazards and adverse effects is included in Table A-1 in Appendix A.

Table 4-1: Technical risks and impacts.

Technical risk	Reservoir type	Description	Possible mitigation
Reduction of available storage volume due	porous rock & salt caverns	Under certain conditions, salt creep can lead to cavern closure and loss of available storage volume (solution-mined caverns) Porous reservoirs may experience volume loss due to compaction following pressure depletion	<ul style="list-style-type: none"> <li>• Pressure control</li> <li>• Cavern depth limits</li> <li>• Monitor cavern morphology</li> <li>• In-situ stress models and geological mapping</li> <li>• Evaluate halite properties that influence creep rates</li> </ul>
Fulfilment of storage volumes (fast or seasonal cyclical or strategic storage)	porous rock & salt caverns	The initial (original) high pressure of some depleted natural gas reservoirs (250-400 bar) may not be used as maximum working pressure for hydrogen storage due to technical and economic reasons	<ul style="list-style-type: none"> <li>• Optimization of the number and location of wells, or the number of caverns.</li> <li>• combined use of storage in porous reservoir and salt caverns should be investigated.</li> <li>• Upscaling of salt cavern clusters should also be investigated.</li> <li>• Be aware of compression requirements (especially where storage site is at high pressures)</li> <li>• Develop reservoir management strategy</li> </ul>
Reaction of hydrogen with minerals in host rock	porous rock & salt caverns	Hydrogen promotes oxidative or reductive reactions depending on the nature of minerals, pH and redox potential. This can affect reservoir properties (e.g., effective porosity and permeability) and well completion materials.	<ul style="list-style-type: none"> <li>• Select storage lithologies that will not react with hydrogen and ensure only low concentrations of oxygen enter the reservoir</li> </ul>

Fulfilment of the flow performances (fast or seasonal cyclical or strategic storage)	porous rock & salt caverns	Variation in hydrogen flow performances due to changes in i) size and interconnection of porous and production interval, e.g., due to geochemical/microbial reactions or reservoir compaction, ii) presence of other gas/liquid phases, iii) permeability and porosity because of geo- and biochemical processes, iv) mixing issues because of residual gases in the reservoir/cavern, v) hydrogen loading with liquids (water, hydrocarbons) from the storage, vi) changes in wettability.	<ul style="list-style-type: none"> <li>Monitoring of flow performances and purity of the gas withdrawn.</li> </ul>
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Table 4-2: Safety risks and impacts.

Safety risk	Reservoir type	Description	Possible mitigation
Salt creep leading to well integrity problems (cavern)	salt caverns	Salt movement has been observed to squeeze or stretch wells, which could potentially result in leakage	<ul style="list-style-type: none"> <li>Well integrity plans being up to date and followed</li> <li>Understanding salt creep</li> <li>Extra strong casing and connections</li> </ul>
Reactivating faults	porous rock & salt caverns	Fluctuating pressures and introduction of different fluids might lead to reactivation of existing faults potentially causing induced seismicity.	<ul style="list-style-type: none"> <li>Pre-operation geological studies and stress analysis</li> <li>Detailed mapping of faults on seismic data</li> <li>Seismic monitoring</li> <li>Monitoring wells in adjacent sandstone layers (for porous storage)</li> </ul>
Generation of H <sub>2</sub> S	porous rock & salt caverns (with anhydrite)	H <sub>2</sub> S could be produced via some geochemical or microbial reactions involving hydrogen	<ul style="list-style-type: none"> <li>Avoid storage in host rocks where H<sub>2</sub>S could be formed</li> <li>appropriate post-production processing of hydrogen to reduce H<sub>2</sub>S to acceptable levels</li> <li>appropriate well design (casing, cements, MMV)</li> </ul>
Air emissions	porous rock & salt caverns	CO <sub>2</sub> , NO <sub>x</sub> , H <sub>2</sub> thermal emissions may be associated with parts of the hydrogen storage supply chain	<ul style="list-style-type: none"> <li>Design and employ low-carbon or renewable energy solutions to minimise emissions</li> </ul>

Table 4-3: Economic risks and impacts.

Economic risk	Reservoir type	Description	Possible mitigation
Reduction in available rocks for storage	porous rock & salt caverns	Sterilisation of available subsurface strata due to other uses of the subsurface (e.g., mineral production, waste disposal, other energy technologies)	<ul style="list-style-type: none"> <li>Effective planning of the use of the subsurface</li> </ul>

Loss of performances (withdrawal, injectivity)	porous rock	Geochemical reaction and/or microbial reactions can reduce the pore space and permeability in the reservoir (mostly around the wellbore) by clogging.	<ul style="list-style-type: none"> <li>• Use of chemicals or mechanical methods. For mechanical methods a short period of high injection/withdrawal to create a pressure environment around the well that could kill the microbial population causing the clogging.</li> </ul>
Contamination (mixing) and migration of stored hydrogen into the cushion gas	porous rock	Hydrogen contamination may result in post processing of gas to ensure required quality Losses by diffusion, losses via chemical reactions forming new gas components or precipitation (although cushion gas may still be recovered).	<ul style="list-style-type: none"> <li>• Minimise potential for contamination by use of hydrogen or alternative cushion gas compositions</li> <li>• Lower hydrogen purity to reduce chemical and/or microbial reactions</li> <li>• Selection of porous reservoirs with suitable properties (e.g., low vertical permeability, avoidance of reservoir rocks with particularly reactive mineral compositions)</li> <li>• Optimise storage design (e.g., well placement, perforated intervals) and operational schedule</li> </ul>
Abandonment costs	porous rock & salt caverns	Costs of site abandonment rise due to unforeseen technical or safety issues	<ul style="list-style-type: none"> <li>• Devise credible abandonment plans at site inception, based on realistic technical and safety models and information</li> </ul>
Loss of cushion gas to formation	porous rock	Cushion gas becomes irretrievable in formation and is a sunk cost	<ul style="list-style-type: none"> <li>• Develop models of cushion gas behaviour that allow reduction in loss of cushion gas to formation</li> </ul>
Cost of cushion gas	porous rock & salt caverns	Large volumes of cushion gas may present an unacceptably high capital cost	<ul style="list-style-type: none"> <li>• Use of lower cost cushion gas compositions (i.e., N<sub>2</sub>, CO<sub>2</sub> and CH<sub>4</sub>).</li> <li>• Understand the working gas to cushion gas ratios at different ranges of working pressures to optimise gas utilisation in the storage unit</li> <li>• Upgrade surface infrastructure to improve facility efficiency</li> <li>• conduct site-specific reservoir simulation for site optimisation</li> <li>• Develop a thorough compressor scheme to deliver desired flow rates at lower pressures</li> </ul>

## 4.8 Summary of findings and recommendations

There is ample experience with the assessment of storage performance of natural gas storage sites and the optimization of productivity in oil and gas wells. The performance of UHS in salt caverns can be modelled and is not complicated by the heterogeneities that are typical for porous reservoirs. For the latter, performance is much more challenging to assess as there are still substantial knowledge gaps regarding the thermodynamic and flow-dynamic behaviour of hydrogen in the porous matrix. Most experiences for pure hydrogen result from laboratory experiments. Below a brief summary is given on storage performance related challenges that need further attention in research and demonstration by operators and research institutions. These actions are needed to reduce the technical and economical risks and uncertainties associated with the underground hydrogen projects. They are strongly interlinked with the challenges and recommendations on design of wells and storage facilities (Chapter 6) and storage economics (Chapter 7)

### Demand profiles and operational parameters and limits

- In line with UHS demand profiles, further definition of maximum storage (working) pressures, cycle rates and deliverability from subsurface facilities is needed.
- The impacts of different cushion gas compositions and their effect on hydrogen quality, hydrogen flow, economics, and surface and subsurface facilities must be better understood.
- Further investigation is needed to determine if and how UHS can be effectively and economically developed and operated in depleted hydrocarbon reservoirs with residual gas/condensates/oil in place.
- Improve understanding of potential surface uplift/subsidence and induced seismicity arising from UHS and establish safe operational parameters to minimize the occurrence of such effects and ensure that impacts do not exceed local safety and environmental norms.
- Develop monitoring strategies and define leak-rate criteria for cavern integrity testing.

### Modelling performance

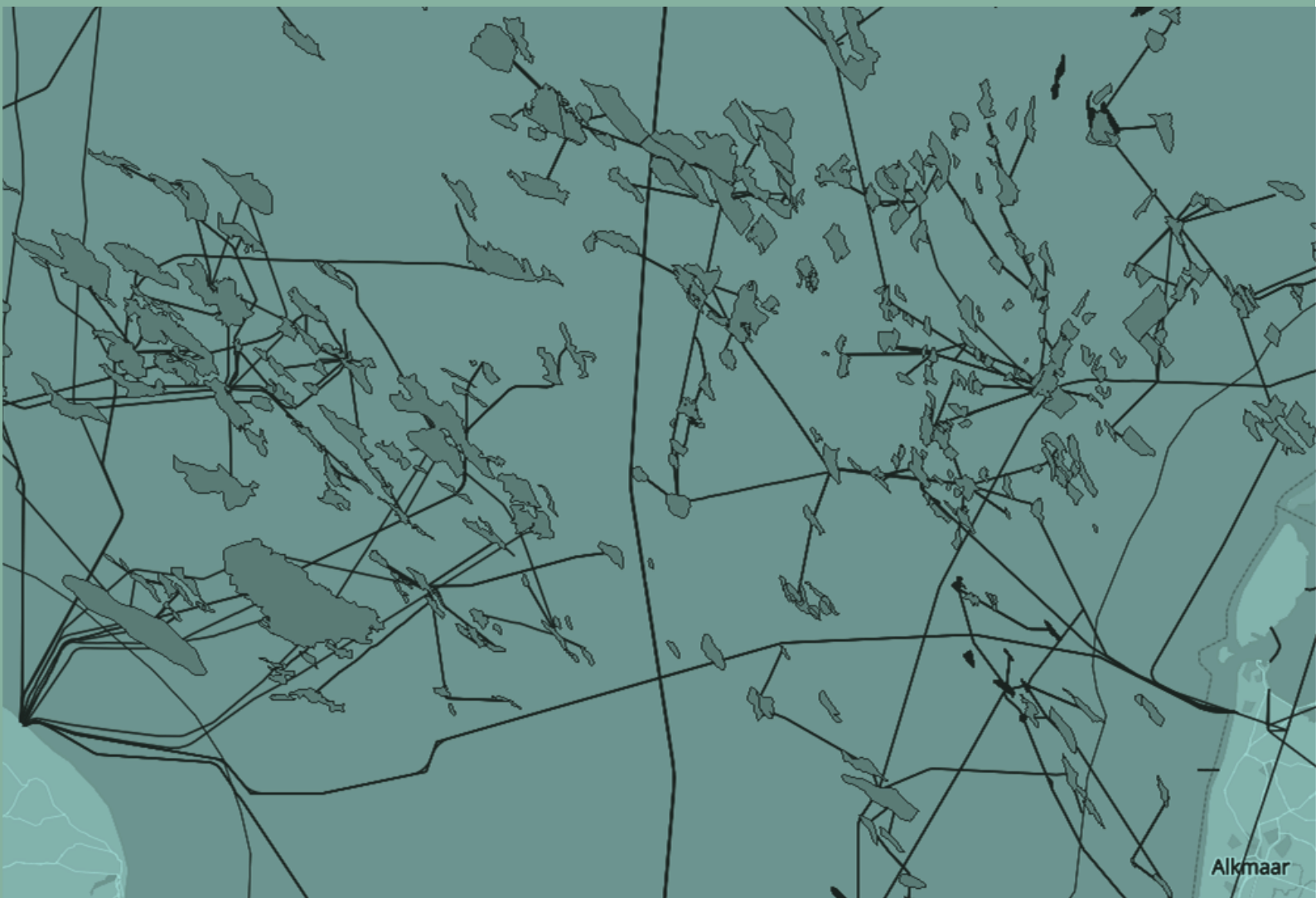
- Determine plausible interactions between the reservoir/well performance and surface (treatment) facilities that could occur (e.g., optimising pressure ranges and cyclicity, gas composition and contamination).
- Improve understanding of hydrogen flow behaviour at the pore-scale and how to upscale such results to reservoir scale. Use real field data to improve and validate (match) numerical models.
- Establish coupled models which are able to reliably evaluate and predict performance impacts from multiple processes. For instance, solubility of hydrogen and alternative cushion gases in formation fluids, hydrogen contact angles on flow in porous media, mechanisms for residual trapping in porous rocks, and potential for microbial stimulation and geochemical reactions.
- Assess the interactions between reservoir characteristics and storage performance including the impact on efficiency of storage operations and hydrogen recovery.

### Risk reduction and performance optimization

- Investigation of mixes of natural gas and hydrogen which may result in more favourable transport and phase properties and energy output; Experimental approach may establish viscosity and phase behaviour.
- Investigation of conditions inside the reservoir that enhancing the microbial conversion of hydrogen to methane inhibiting H<sub>2</sub>S formation.
- Investigation of sustainable biocides and associated environmental risks.

# CHAPTER 5

## Geological Characterization, Screening and Ranking



Storage potential

Influencing factors for site screening

Screening criteria and workflows

Examples of storage capacity estimates



## 5 Geological characterization, screening and ranking

### 5.1 General introduction

All underground activities, regardless of purpose or technology, depend on the screening and selection of suitable sites where deployment is deemed technically, economically, environmentally and socially viable. This chapter discusses several general principles, criteria and examples that are applied and used to regionally evaluate and rank portfolios of potentially suitable candidates for underground hydrogen storage. Such evaluations provide a starting point for storage operators to further select and mature specific candidates for actual deployment. Policy makers and spatial planners may use these evaluations as a guidance to design and lay-out future energy systems components (e.g., transport networks, production facilities) or to support further decisions on where and in what form underground storage activities may be allowed and integrated in the local context.

### 5.2 Theoretical, effective, practical and matched storage potential

The regional screening and selection of suitable and preferred storage candidates is typically performed in a staged approach where potential sites are progressively ranked and filtered at consecutive levels represented as shown in Figure 5.1 in the so-called storage resource pyramid [217]. Each level in this pyramid represents specific selection principles and criteria, which are narrowing down the suitable candidates from bottom to top. The various storage potential levels are further explained below.

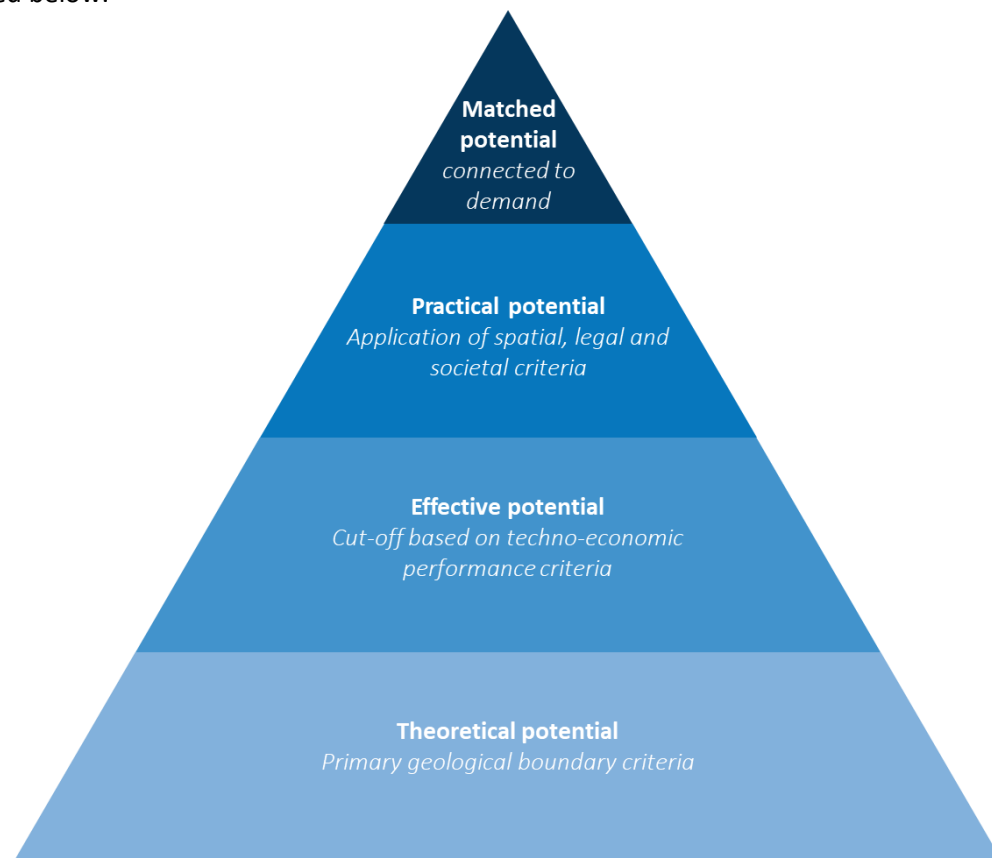


Figure 5-1: Representation of the storage resource pyramid, modified after [217].

- The **theoretical storage potential** is determined by evaluating the site-specific suitability of rock formations for UHS, based on principal geology boundary conditions only. In most cases this involves a combination of firm and absolute criteria and characteristics – often referred to as the “geological play” – that are determined by natural geological processes and that cannot be changed through human intervention. For underground storage of hydrogen and natural gas this concerns either:
  - the presence of a porous rock formation (e.g., sandstone) with a sealing, gas-tight layer (e.g., shale or rock salt) on top, both of which occur within a confined geological structure (e.g., a trap) such that injected gases are laterally and vertically contained.
  - the presence of a sealing (gas-tight) rock formation or rock body (e.g., a thick rock salt layer/pillar or a hard rock formation) suitable for creating caverns or tunnels in which injected gases can be contained.

While many assessments consider depleted gas reservoirs as primary targets for UHS in porous rock formations [148, 218], there are differing views on whether oil fields and gas fields containing condensates may be suitable (e.g., [175, 219, 220]) or not (e.g., [148, 218]).

- The **effective storage potential** considers additional selection criteria for ranking and selection of potential sites based in their estimated or modelled technical and economic performance (see Chapter 4 and 7). These criteria result in ranges that are considered more or less favourable, taking into account the intended type of deployment (e.g., demand profile) and technical design (e.g., well specifications, see Chapter 6). Typical characteristics for evaluation are primary geological parameters such as porosity, permeability, depth, as well as derived parameters such as estimated production rates and working gas volume.
- The **practical storage potential** considers further non-geological aspects that may exclude certain regions or locations from hydrogen storage deployment due to existing surface restrictions (e.g., nature protection areas, urban areas) or interfering uses at or below the surface (e.g., groundwater extraction, critical infrastructure projects, existing storage or extraction activities in or adjacent to the evaluated storage site). Some sites may be excluded because of poor accessibility of the site or because disturbance from construction activities, induced surface impacts (subsidence, seismicity) or climate and air quality impacts (CO<sub>2</sub>, NO<sub>x</sub>) is not allowed.
- Finally, few sites may remain as **matched capacity**, which implies that these can be connected to an energy network for supply and demand, or directly to an end-user of the storage services.

There is no standard method to determine the potential and suitability for hydrogen storage although published studies generally follow more or less similar workflows. Learnings can be made from volume and performance estimates for hydrocarbons, natural gas storage, CO<sub>2</sub> storage and other novel energy technologies such as Compressed Air Energy Storage (CAES). For salt caverns the limited number of existing operational facilities may give some information on the characterisation and screening criteria of storage facilities in solution-mined caverns. There is however a substantial degree of uncertainty in how the experiences of these locations can be generalized to regional or national scales. For storage in porous rocks, evaluations rely on numerical simulations, or on using proxy studies such as storage of natural gas or models for CO<sub>2</sub> storage. For experimental data the upscaling from laboratory results to a site scale or to reservoir-scale models remains a challenge. In [90] it is recommended to establish criteria relevant specifically to hydrogen when identifying new storage targets in porous rocks. While depleted gas reservoirs may be considered when identifying suitable targets for porous rock storage of hydrogen, [148, 218] state that oil fields and gas fields containing condensates may be inappropriate due to the potential of geochemical interactions between hydrogen and any residual hydrocarbons, when hydrogen may convert to methane or dissolve in oil. However, this is not universally accepted, with [219] considering gas condensate reservoirs as potential storage targets, and with [175, 220] considering depleted oil reservoirs in their assessments.

### 5.3 Influencing factors for site screening

#### 5.3.1 Salt formations, structures and potential for cavern development

The criteria required to map, characterise and rank potential underground hydrogen storage sites are well established for storage in solution-mined caverns, e.g., [221]. These are influenced by the quality, depth, type of salt structure and available thickness of halite in which caverns could be located. Unlike porous reservoirs, storage of hydrogen in salt caverns is less effected by multi-phase phenomena as halite is much less reactive than siliciclastic reservoirs and residual water gathers at the bottom of the cavern, but more influenced by complex thermodynamic relationships. The temperature of a cavern is related to the depth in the subsurface due to the geothermal gradient, with hydrogen expanding at higher temperatures [191]. The depth of storage also influences the pressure at which hydrogen can be stored, injected and produced from a cavern. An increased depth of a storage cavern therefore results in an increase in hydrogen volume, due to increased temperature (decrease in mass) and an increase in mass due to an increase in pressure (increase in mass); typically, it is pressure that has the greatest effect on the resulting gas volume.

The effect of cyclicity and associated pressure changes can be understood using published data from operational hydrogen storage caverns and using examples from natural gas and brine production caverns as a proxy for hydrogen storage in caverns. There are, however, uncertainties related to the impact of operating a salt cavern as hydrogen storage site, as a chemical feedstock (as is currently employed) or as an energy carrier, which may require higher frequency storage cycles and withdrawal/injection rates. Numerical models and code can evaluate optimal scenarios for hydrogen storage and recovery. These can include the round-trip energy efficiency of storage cycles that can underpin predictions of the cost of operating storage facilities.

Cavern development is strongly influenced by local stratigraphic variability (e.g., cavern morphology in response to naturally occurring beds of mudstone, anhydrite and other insoluble material; or beds of sylvite or other higher soluble evaporites). In general, taller, smoother caverns can be developed in salt diapir structures while bedded halite results in caverns of limited height with indurated margins [222]. It is also determined by the type of circulation (direct/reverse) during solution mining [223]. Geological structure (dip and any healed faults) and natural stress can also influence cavern development, resulting in caverns becoming elongated up-dip or along the lowest in-situ principal stress directions. In [178] it is indicated that cavern migration, microseismicity, surface subsidence and long-term subsidence can all be related to the construction of caverns in the subsurface. Beside the availability of fresh water and the ability to dispose brine safely, constraints on the land available for the generation of caverns are summarised in [178], and include:

- Urban areas,
- Rural areas,
- Major fault zones,
- Areas of natural beauty; designated protection areas,
- Major infrastructure,
- Distance from limits of salt bodies, and
- Availability of waters to wash caverns and the disposal of brines following solution mining are additional developmental constraints.

These influences result in the theoretical evaluation of storage capacity that can be associated with a high degree of uncertainty, especially where critical data are lacking (e.g., a lack of exploration wells can lead to uncertainties in halite composition and structure). Therefore, detailed geological characterisation should be undertaken prior to development of solution-mined cavern facilities.

### 5.3.2 Depleted gas fields and deep saline aquifers

Storage facilities in porous rock formations are attractive as halite accumulations suitable for cavern development are more geographically restricted. Additionally, the volumes offered by storage in porous rock formations (e.g., depleted natural gas reservoirs) are much greater than those in solution-mined caverns (although production rates may be lower, and cushion gas requirements may be larger, impacting on the capital costs of establishing an operational facility). Saline aquifers offer even greater potential storage volumes, but may require additional characterisation to ensure an adequate seal and containment structure are present which may require an extensive seismic acquisition/drilling programme. The potential storage capacity offered by porous formations is likely to be far greater than the total hydrogen demand in many countries irrespective of the specific use-requirements of industry, and even individual fields are likely far larger than required (e.g., multi-TCF gas or many hundreds of millions of barrels of oil equivalent).

Depleted natural gas reservoirs have an established and proven capability to store natural gas, giving some confidence to their ability to contain hydrogen. For natural gas reservoirs, there may already be a substantial body of data available to characterise the storage volume, with key parameters such as reservoir temperature, in-situ stress, structural data (faults, dip and closures), porosity and permeability, geochemical and geophysical characteristics and properties of the cap rock already known. However, the effect of different gas cycling in terms of volumes and pressures are not well understood and together with well integrity issues must be carefully evaluated using numerical models to ensure reservoir behaviour can be predicted [151, 176, 185]. According to [37, 224] offshore hydrogen storage reservoirs that are at least 1,500 m deep should allow for hydrogen densities of 10 kg/m<sup>3</sup>.

## 5.4 Screening criteria and workflows

### 5.4.1 Screening criteria and workflows: Solution mined caverns

Several studies have been conducted to estimate storage capacity in solution-mined caverns. The volumetric calculations are informed by the development of caverns for brine production, development and performance of caverns for natural gas storage, numerical models developed to estimate capacity of caverns for CAES schemes, and the few operational caverns that are used for hydrogen storage.

Considerable effort has been deployed in the mapping out of halite accumulations that may be suitable for the development of solution-mined caverns. In the early 2000s, this was mainly done in support of natural gas storage, although more recently it has been associated with the development of CAES as a low-carbon energy storage technology, and hydrogen as interest in establishing hydrogen economies in order to meet net-zero carbon ambitions has developed.

In [187] a method is described with which the storage capacity for CAES schemes in parts of England has been estimated. Building on this method, the EU Elegancy project [192, 225] adapted this approach to estimate storage capacity for hydrogen storage across parts of Europe, applying some of the thermodynamic rules for hydrogen to calculate hydrogen storage volumes, injection and production rates for individually modelled caverns. The method employed used mapped accumulations of halite within which viable caverns could theoretically be constructed. Their depth and cavern dimensions allowed the pressure and temperature of the caverns to be calculated, allowing the working gas to cushion gas ratio, and the amount of energy stored to be assessed. Finally, caverns were screened by their proximity to geological faults and margins of halite bodies, and non-geological factors such as surface infrastructure and environmentally sensitive areas.

A series of publications focuses on the generation of models to understand the potential for cavern storage in the Shandong and Jiangsu districts of China. In [226] the effect is reviewed of insoluble material in the halite succession and leaching processes on cavern morphology and available storage volumes. The effect of insoluble material on cavern volumes is considered in [227]. This study considers halite successions where the insoluble content exceeds 20%, which can reduce cavern volumes achieved by approximately 35%, although a maximum insoluble content to achieve viable caverns is not considered. For halite successions with greater proportions of insoluble material, the construction of caverns with a horizontal long-axis, or U-shaped caverns are considered in [228, 229]. Where cavern development becomes limited by the quality of available halite, the development of caverns in higher-insoluble successions may be considered. Modelling studies reported in [230] indicate that estimated cavern volume reductions in the order of 60% may be encountered where insoluble contents reach ca. 45% of the halite succession. The development of caverns in halite formations between 2,740 – 2,940 m is considered in [231]. They note that Cavern 1 at Eminence Dome, located at a depth of approximately 1,750 – 2,000 m, lost approximately 40% of its original volume after just 20 months of operation, and consider optimal operational parameters to avoid such reductions in cavern volumes, including operation without cushion gases.

A workflow estimating storage potential for much of Europe was employed in [178]. The following parameters were used:

- Bedded halite- minimum thickness of 200 m.
- Minimum thickness of halite overlying a cavern: 75% cavern diameter.
- Minimum thickness of halite beneath a cavern: 20% cavern diameter.
- Height to diameter ratio of a cavern: 0.5.
- Assume a 'capsule' shaped cavern at depths less than 1,200 m and 270 bar overburden pressure.
- (Bedded halite) Minimum cavern volume 500,000 m<sup>3</sup>, diameter 84 m and height 120 m.
- (Domal halite) Minimum cavern volume 750,000 m<sup>3</sup>, diameter 58 m and 300 m height.
- Pillar thickness 4 times cavern diameter (equates to 232 m for domal caverns and 336 m for bedded halite caverns).

The proposed Analytical Hierarchical Process was used in [220] to map formations in Poland. Relevant factors were ranked in the assessment of underground hydrogen storage in solution-mined caverns and porous rocks, with a weighting of parameter calculated (given in brackets). In halites (both bedded and domal): Reservoir lithology (33.2%), Stage of exploration (32.1%), Type of salt deposit (12.2%), Reservoir volume (10.2%), Depth of reservoir (6.3) and Geothermal gradient (6.0%).

### 5.4.2 Screening criteria and workflows: Porous rock storage

There are many studies which have assessed the capacities, volumes and performances of potential sites for UHS development. Many are listed in Section 5.5. Depending on the level of detail, available data, type of reservoir and development, different approaches have been followed to screen these sites and estimate capacities. Below two examples are provided for screening criteria as they have been applied for UHS in porous reservoirs.

In [20] as part of the Hystories project [33], identified screening criteria include:

- Storage volume meets anticipated storage needs.
- Structures have an effective seal and are
  - within viable depth ranges,
  - not compromised by geological faults,
  - such that these retain hydrogen in a suitable trap,
  - not compromised by surface or subsurface infrastructure.

Additional reservoir criteria were identified in [232] for the screening of depleted fields in the Dutch sector of the North Sea and onshore, including:

- Natural gas fields,
- Developed and accessible through production wells at the time of evaluation,
- Minimum depth 1,000 m (TDV),
- A permeability higher than 0.1 mD (i.e., no stimulation required)
- A transmissivity >100 mD.m,
- A Gas-Initially-In-place (GIIP) volume of less than 30 billion m<sup>3</sup> (due to the likely required large cushion gas and geological complexity of large fields),
- No significant amounts of H<sub>2</sub>S (<<10,000 ppm),
- Production data from active gas storage sites and depleted gas fields in hydrocarbon producing regions.

The amount of residual gas in a depleted gas field or an UGS field might be considered as an additional criterium as it may possibly decrease the volume of cushion gas that needs to be injected in order to reach the required minimum pressures for storage operations.

The potential flow performance and working and cushion gas volume for hydrogen for the large portfolio of natural gas fields in the Netherlands were calculated, using standard empirical functions that describe gas flow behaviour and pressure depletion in layered porous reservoirs and in wells with a radial flow [197, 233]. For the calculations, a set of elementary input parameters was collected from natural gas extraction data: GIIP, initial reservoir pressure, average reservoir permeability, thickness, depth and temperature, drainage radius, reservoir shape factor (Dietz), tubing length and diameter, fraction reservoir perforated, wellbore radius, mechanical skin factor and gas composition. A standard maximum wellhead drawdown and a threshold and cut-off flow rate of 1 million m<sup>3</sup>/day were considered to calculate the working gas volume. The lack of operational storage hydrogen facilities in porous rock formations results in a ranking of sites having to be informed by a top-down approach (i.e., assuming rather than gathering operational data such as cyclicity and pressure ranges, injectivity and productivity). Storage ranking schemes have been developed in association with CO<sub>2</sub> storage (e.g., the development of Storage Readiness Levels, SRL [234])

A study focussing on accommodating hydrogen produced by offshore wind, reported in [235, 236], estimated the capacity of offshore gas reservoirs in the UK sector of the North Sea. They used exploration and production data and compared methods that based storage volume calculations on available pore space, and gas-initially-in-place and recoverable gas volume calculations. This study did not specifically consider if fields were suitable for hydrogen storage (e.g., some fields are likely too large to achieve satisfactory storage performance or are located long distances from the coast and would require substantial compression of hydrogen before transport to end use locations which may impact on cost). Using available pore space (derived from the CO<sub>2</sub>Stored dataset [237]) resulted in an estimate of 6,900 TWh of working gas in 95 gas fields (with 85% of the capacity on the southern North Sea). Using GIIP and recoverable gas volumes (importantly, assuming cushion gas comprises 50% of the storage volume, with 20% of this being hydrogen to mitigate mixing between stored hydrogen and residual hydrocarbons), 2,662 TWh of hydrogen storage was calculated to be present in 41 fields that are currently connected to gas terminals.

The Hystories project indicate scoring criteria for porous rocks to include:

- Adequate reservoir thickness,
- Well-defined structure; sizeable closure height,
- Caprock properties are gas-tight,
- Within the storage unit, storage units have porosities and permeabilities that are adequate,
- Production mechanisms are adequate,



- Depth of storage allows for pressure ranges that align with supply to national transmission systems,
- Formation fluids do not degrade quality of hydrogen beyond acceptable limits.

Additionally, the Hystories project also recommends multiple geological and reservoir selection criteria, including geometry of storage unit, petrophysical attributes, tectonic regime, and detail on formation/reservoir fluids.

As part of the calculations for Polish storage, [220] estimated the importance of variables (given in brackets) for saline aquifers and oil or gas reservoirs:

- In saline aquifers: Tectonic activity (36.25%), Lithology of overburden (34.14%), Stage of exploration (16.87%), Depth (7.87%), Pore volume of reservoir (4.88%).
- In gas or oil fields ('hydrocarbon deposits'): Lithology of overburden (36.74%), Tectonic activity (24.09%), Deposit form (15.98%), Pore volume of reservoir (13.11%), Depth (5.09%), Stage of exploration (4.99%).

## 5.5 Examples of storage capacity estimates

### 5.5.1 Theoretical Estimates of Capacity

Chapter 4 introduces various approaches and aspects used to estimate storage volumes and performance of injection and withdrawal. There is a growing number of studies which have assessed storage capacities and geological potential. Some examples are given below:

#### Europe:

- The storage potential for France, Germany, Netherlands, Romania, Spain and the UK was assessed in the Hyunder project [238]. This study investigated the potential hydrogen production that could be achieved from surplus electricity, with storage being feasible in these countries.
- The HyUSPre project presents the results of a storage capacity assessment with an estimation of the theoretical hydrogen storage capacities in European UGS sites developed in porous reservoirs [239]. The capacity for currently operated sites is 664 TWh and could increase to 747 TWh if planned UGS sites are considered as well. Half of the capacity is located in Ukraine, Italy, and the Netherlands.
- The Hystories project estimated the total theoretical hydrogen storage capacity of 750 identified porous rock traps (both gas fields and saline aquifers) across Europe [240]. The resulting capacity for the EU27 and UK is estimated to be 6,925 TWh, of which 2,725 TWh is situated in the 506 onshore traps. Only 0.4% of these capacities is situated in deep saline aquifers.
- A consistent method to investigate the theoretical potential of cavern storage across Europe, in terms of energy density in kWh/m<sup>3</sup>, has been developed [178]. It splits the assessments between onshore, offshore and 'onshore- constrained' areas, which are within 50 km of shore (acknowledging increased costs of brine disposal in-land). It is concluded that the hydrogen storage potential in Europe is 84.8 PWh, of which 42% is located in Germany (35.6 PWh), and 12% (10.4 PWh) in the Netherlands and 11% (9.0 PWh) in the UK. Approximately 27% of the total capacity is located onshore, with the majority of this being present in salt domes in Germany.

#### United States

- A recent study by [241] evaluated existing UGS facilities in the United States. It is found that these facilities, if converted to UHS, could store in total 327 TWh of pure hydrogen, which would be 23.9% – 44.6% of hydrogen demand in 2050.

### Individual country assessments

- An assessment of the potential for storage caverns developed in salt domes in Poland concluded that five individual caverns could process, store and deliver hydrogen to meet in excess of 3% of the annual energy production [242].
- In Poland, in another study, 11 potential storage sites (halite), 4 oil fields, 17 gas fields and 14 aquifer sites have been identified [220].
- The hydrogen storage potential for depleted hydrocarbon fields in the Netherlands was estimated in [232] to include 93 billion m<sup>3</sup> (i.e., 277 TWh) in onshore fields, and 60 billion m<sup>3</sup> (i.e., 179 TWh) in offshore fields. They also considered cavern storage of hydrogen, estimating 14.46 billion m<sup>3</sup> working gas volume (43.3 TWh).
- An evaluation of the potential for salt cavern storage in Romania identified four regions where storage may be focussed, based on geological conditions and brine disposal facilities [243].
- Selected regions in northern Germany were identified for the storage of 27 TWh of energy in existing caverns currently used for natural gas storage [4].
- The Elegancy project [225] reviewed potential onshore hydrogen storage potential in caverns in the UK. They estimated that, for the Cheshire, east Yorkshire and Wessex areas, there is the theoretical potential for 2,971 TWh of storage. The parameters giving most variability to these figures were available thickness of halite, halite depth, content of insoluble material in the halite succession, geothermal gradient and density of the overburden.
- For UK, the seasonal storage of hydrogen in the Rough offshore facility has been modelled [183]. It is found that the facility has a volumetric capacity of 48 billion m<sup>3</sup> and can operate with delivery pressures of 5 – 10 MPa, giving an emptying period of 120 days. The facility can give 42% of the energy capacity in hydrogen than that provided with natural gas; the emptying period of 120 days can give around 100 GWh/day (40% the deliverability of natural gas). The study found that there were potential losses from the storage complex associated with biological activity and leakage, giving 3.7% and 0.035% losses respectively, in addition to loss via conversion to H<sub>2</sub>S where sulphur was a mineral component of host rock.
- Other studies have conducted site selection analyses for France [244], Germany [245], Russia [246], and Spain [247].

#### 5.5.2 *Field pilot and demonstrator sites, major projects and modelling studies for hydrogen storage research and development*

Several research sites are operational or in development that will be relevant to understanding processes relevant to hydrogen storage in the subsurface (Table B-2, Appendix B). There have also been numerous large projects, with results being publicly available for some (Table B-3, Appendix B). In addition to the field pilot and demonstrator sites and projects listed above, in [216] a comprehensive list is given of underground hydrogen storage modelling reviews.

### 5.6 Summary of findings and recommendations

There is a growing number of studies which provide regional evaluations of potential sites for underground hydrogen storage. Such evaluations focus on UGS facilities that may be converted to UHS, depleted gas fields, undeveloped traps in aquifers (porous rock) and salt structures in which storage caverns may be developed. Different methods and criteria are applied in these studies to screen sites and estimate associated capacities and it is generally difficult to make a good comparison between these studies.

The results mostly represent theoretical capacities. While these estimated capacities appear to exceed the expected future demand for storage capacity, it should be realized that the finally realizable potential will be substantially reduced by further techno-economic cut-off criteria, spatial,

environmental and legal limitations, and the possibilities to connect storage sites to the hydrogen transport network and end-users.

Site screening, ranking and capacity assessments are crucial for a timely, effective and socially accepted planning, preparation and upscaling of UHS and for meeting the demand requirements in the decades to come. This is not only relevant for the technical development of sites but also important for optimally planning the entire energy system. The information resulting from site screening are a basis for enabling public participation processes and transparent decision making. To this end, the existing screening methods and criteria should be extended with additional criteria which allow for a more comprehensive ranking based on practical and social criteria. The screening and planning of sites should also consider the entire life cycle of a storage site, including potential long-term impacts that may occur long after the operations have ceased.

# CHAPTER 6

## Facilities and Wells



- Well designs, materials and integrity
- Top-side facility design and engineering
- Operational parameters and limits
- Safety and monitoring concepts
- Impacts on development and operations

## 6 Facilities and wells

### 6.1 General introduction

This chapter presents the current knowledge and state-of-art for the construction and operation of storage facilities, the completion of injection/production wells and the applicability of safety and monitoring concepts during the various stages of development and operation.

An underground storage facility for hydrogen consists of a storage reservoir (one or more salt caverns, or a depleted gas reservoir), wells for injection into and withdrawal from the storage reservoir, pipelines connecting the wells to surface facilities above-ground and the connections to the transport network (see Figure 6-1). In surface facilities, hydrogen is compressed prior to injection into the storage reservoir, while post-withdrawal it is dried and purified while being expanded. Drying is required because the hydrogen picks up moisture while stored underground. The purification of the hydrogen is an important step to ensure that the quality of the hydrogen meets the specifications for re-injection into the transportation network. A storage facility commonly also includes a control room, offices, and in case of a manned offshore facility, possibly some living quarters (if manned) and a helideck, yet these are not shown in Figure 6-1 and will not be further elaborated on in this chapter.

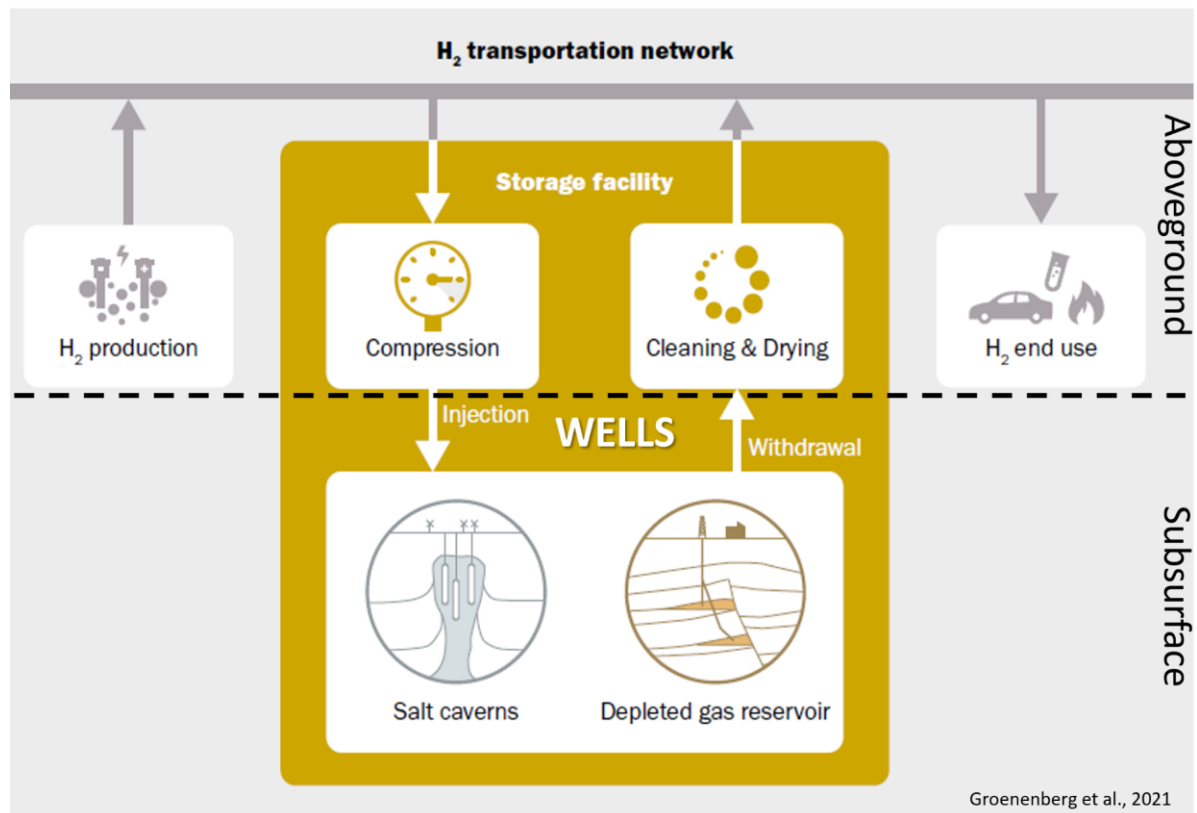


Figure 6-1: Schematic diagram of the key components of a hydrogen storage system [185].

Figure 6-2 displays the process flow during injection and withdrawal in a manned facility. At injection (left diagram in Figure 6-2), hydrogen flows from the pipelines of the hydrogen transport system to the storage facility, where it is first filtered and metered. The hydrogen transport system connects hydrogen production facilities with facilities where hydrogen is consumed (see also Figure 6-1). While the pressure level in the transport system will probably be in the range of 30 – 50 bar, the storage pressures are commonly (much) higher (up to 200 bar for salt caverns, and possibly 300 bar for reservoirs). Additional compression and cooling of the hydrogen is therefore required (to

temperatures between 15 – 40 °C), after which it is led via the local pipeline network of the facility to a manifold that distributes the hydrogen over multiple wells, through which it is injected into the caverns or storage reservoirs.

At withdrawal (right diagram in Figure 6-2), hydrogen flows through the wells back to the surface, where first any solids and liquids in the withdrawn stream are separated from the hydrogen gas, after which it is heated, expanded, dried and optionally purified. Once it reaches the required specifications (e.g., purity level, pressure, temperature, dew point), hydrogen is again metered and filtered, and then finally fed back into the hydrogen transport system again.

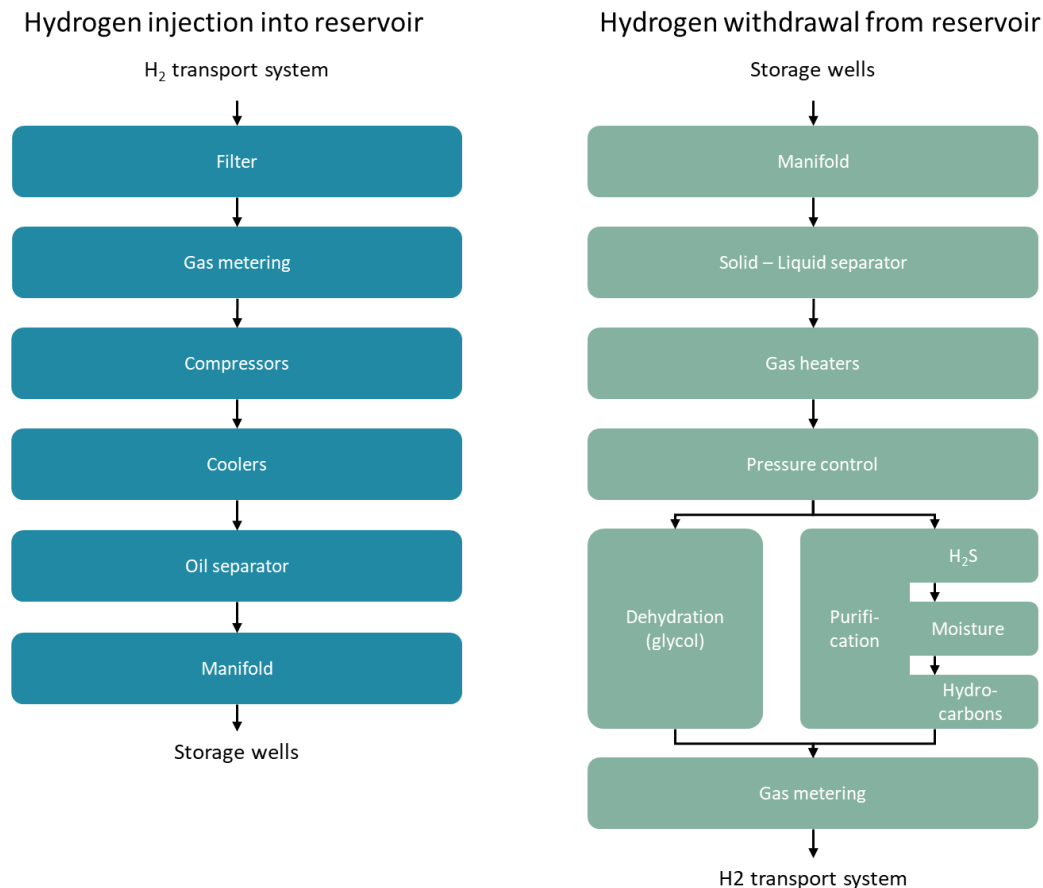


Figure 6-2: Schematic diagram of process flow during injection (top left) and withdrawal (top right) of hydrogen, assuming glycol is used for drying of hydrogen.

## 6.2 Well designs, materials and integrity

### 6.2.1 Well designs

Functional requirements for hydrogen storage wells do not differ from natural gas storage wells, hence their designs are largely similar. However, the materials used and component design require a detailed review, tests, and confirmation or potential modifications prior to their application. This section provides a short description about well and completion designs for hydrogen storage in salt caverns and in porous rock reservoirs (see Figure 6-3). Furthermore, the double barrier philosophy to prevent leakage is reviewed, and how it is implemented in Europe (open annulus) vs. USA (cemented annulus).



Figure 6-3A displays well designs for natural gas storage in salt caverns, in this case in a configuration with two wells in one cavern, which is more the exception than the rule. Commonly salt caverns have only one well, the design of which looks like the right well of the two displayed in the schematic diagram of Figure 6-3A. Key components in the well design are the wellhead, the cemented casing(s), the last cemented casing shoe (LCCS), the tail pipe (through which the gas can flow into and out of the cavern), production tubing and packer, and the (tubing-mounted) subsurface safety valve. Optionally, a second packer can be installed below the production packer to serve as an additional barrier to prevent leakage into the annular space between the casing and production tubing. This annulus is commonly filled with a (corrosion-inhibiting) completion fluid, and pressure in the annulus is monitored at the wellhead to detect leakage. In the US, the use of a fluid-filled open annulus is not common. Instead of the production tubing, a production casing is cemented onto the (outer) casing in the US, i.e., the annulus is filled with cement.

The design of the left well of the two displayed in the schematic diagram in Figure 6-3A differs in that it has an extended liner (and liner hanger, instead of a tail pipe) that extends into the brine at the base of the cavern. The extended liner has zone masters: valves that can be opened and through which the stored gas can flow into and out of the cavern at different depths. A key advantage of this completion type is that it enables cavern de-brining without the need to use a dedicated de-brining string and avoiding snubbing operation, i.e., the installation into and removal of a dedicated de-brining string under gas pressure.

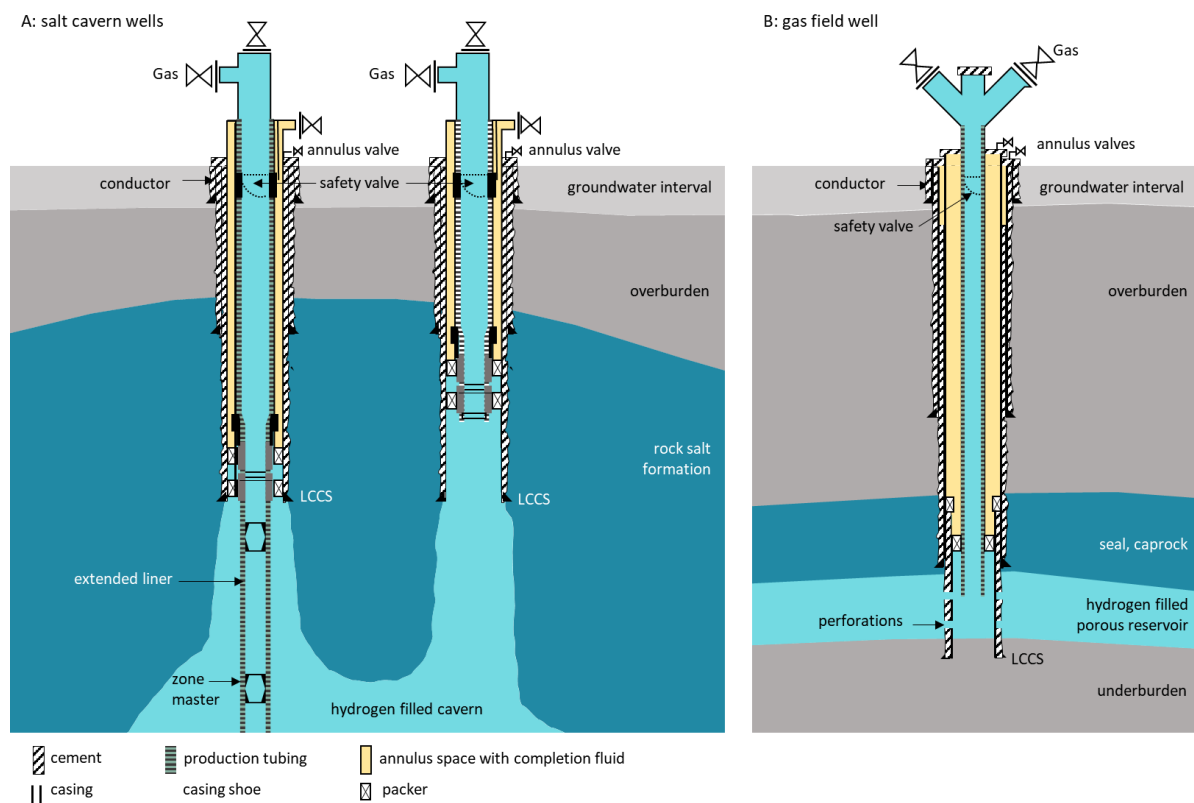


Figure 6-3: Schematic diagrams of well designs for hydrogen storage in (A) salt caverns, modified after [248], and (B) porous rock reservoirs, modified after [249].

The scheme in Figure 6-3B displays the well design of a natural gas storage well in a porous reservoir. Apart from the fact that wells in reservoirs (commonly) reach greater depths, cross more stratigraphic layers, and hence may have more cemented casing sections and more annuli, key differences are the extension of the production tubing into the cased wellbore below the production packer, and the cemented liner (and packer). For example, in a storage well that ends with a 7" liner, there are three annuli: two cemented annuli, between the 13 3/8" and 10 3/4" section and between the 10 3/4" and

the 9 5/8" section, and one fluid-filled annulus between the 9 5/8 "casing and the 7" liner. Also shown in Figure 6-3B are the perforations through the cemented liner that allow the gas to flow into and out of the reservoir, and the sand screens that may have been installed to prevent influx of solid particles into the wellbore. Furthermore, many natural gas storages in porous rocks have horizontal wells to increase reservoir exposure and reduce the number of wells necessary to operate the working gas volume. Horizontal wells are mostly not cemented but instead rely on an open hole completion (with or without liner for stabilization).

The well designs as shown in Figure 6-3 contain multiple barriers to prevent uncontrolled fluid flow (leakage) into the subsurface and through the wellbore towards the surface. These barriers can be divided into primary barriers and secondary barriers. Primary barriers are the production casing, liner and liner cement below the production packer, the production packer, and the completion string below the subsurface safety valve (SSSV). Secondary barriers are the production casing, liner and liner cement above the production packer, the completion string above the SSSV, the wellhead (including casing hanger with seals and wellhead valves, not shown in Figure 6-3), and the production tree (body and master valves). The SSSV is a key component of a gas storage well. Its sole purpose is to automatically close off the well in the event of loss of hydraulic control pressure that would lead to uncontrolled release of the gas (i.e., blow-out). In such situations of pressure control loss, the SSSV is considered a barrier to flow provided its ability to block the flow sufficiently has been demonstrated.

Key concerns for wells in relation to H<sub>2</sub> in general are:

- **Molecule size:** Hydrogen is a much smaller molecule than natural gas, has a high diffusivity, and a low viscosity, and as such it can leak more easily compared to a natural gas molecule, presenting challenges to well barrier design.
- **Chemical reactivity:** Hydrogen is highly reactive, i.e., it can interact chemically with rocks and dissolved components in reservoir fluids. In addition, other reservoir fluids can enhance negative chemical interactions and this may need to be managed accordingly. The presence of hydrogen can also induce microbial activity, causing Microbially Induced Corrosion (MIC) of metal components of wells and surface facilities.
- **Frequent cycling during operations:** Hydrogen stores are expected to inject and extract hydrogen frequently, meaning more frequent pressure and temperature cycling which can fatigue well components, and the near-well area of the reservoir. This is particularly relevant for storage in caverns (salt, lined rock), which are likely to have more frequent injection/production cycles than porous rock stores. Furthermore, in particular for storage in reservoirs, the high volumes of gas being transported through the wells during cycles will increase erosion of flowlines and well components due to co-production of solids (rock particles), and may require constraining flow rates and, thus capacity.
- **Hydrogen compatibility of materials, components, and equipment:** New materials and components may be required that can withstand long-term operations under extended exposure to hydrogen (e.g., fibre optics darkening issue explained later in the chapter) or H<sub>2</sub>S (gas chromatographs have issues measuring hydrogen on H<sub>2</sub>S exposure).

In the next sections below, specific concerns for well materials and components will be listed and topics for providing guidance on and requiring further research will be highlighted.

### 6.2.2 Well materials

There are three major material concerns for hydrogen well materials: metals, elastomers and cements. Of these, the metal and elastomer components are expected to be of primary concern, with cement degradation due to hydrogen exposure so far expected to be of lower concern ( [30, 250] and references therein). Location of these materials in a normal well is shown on the well diagrams in Figure 6-3.

### Key concerns for steels and alloys

These include hydrogen embrittlement (HE), Hydrogen-Induced Cracking (HIC) and blistering. Hydrogen has a strong detrimental impact on the mechanical properties of steel which is known as HE. This can manifest itself in a decrease in ductility and fracture toughness and increase in a steel's susceptibility to fatigue causing cracks from which hydrogen can leak into the environment [251]. Concerns related to HE include HIC and blistering. Several operational factors are listed below that can play a role in increasing the risk of HE and/or HIC and/or blistering, and these are commonly not considered by default in material compatibility research:

- Corrosion due to exposure to extreme salt concentrations, wet hydrogen gas, H<sub>2</sub>S and CO<sub>2</sub> (in reservoir fluids), and activity of microbes, i.e., microbiologically induced corrosion.
- Repetitive changes in pressure (P) and temperature (T), i.e., reduction in competence due to exposure to hydrogen in combination with P, T swings, leading to fatigue and/or failure.
- Erosion when (solid) particles are present in the production stream (reservoirs), requiring sand exclusion mechanisms (e.g., screens) and/or means of limiting flow velocity which can impact performance.
- Corrosion in weakened parts of the production tubing/liner like welding seams.
- Specifically for storage in porous reservoirs, additional concerns for material integrity and selection are co-production of formation water, and the presence of contaminants (H<sub>2</sub>S, CO<sub>2</sub>, CO, N<sub>2</sub>, light hydrocarbons, etc.).

### Key concerns for elastomers (used in packers, see Figure 6-3) and other sealing materials are:

- Loss of mechanical strength and elasticity (ability to respond to rapid compression and decompression).
- Explosive decompression.
- Changes in mass and volume due to component embedding into the material matrix.

### Key concerns for cements are:

- Thermodynamic interaction of hydrogen with cement components.
- Degradation of the mechanical properties (hydrogen-induced chemical alteration).
- Changes in physical properties (i.e., permeability).
- Reduced leak tightness of (different types of) cement, and its interfaces with the rock and the casing, due to exposure to hydrogen. For example, risk of leakage of hydrogen along the cement-to-formation interface due to formation of micro-annuli during cyclic pressure and temperature changes in combination with very low viscosity of hydrogen.
- Different cement composition at different depths (e.g., at LCCS and in casing strings upwards to surface) to avoid mud contamination in salt caverns.
- Influence on the hardening process of cement in newly drilled wells in hydrogen bearing reservoirs.
- Optimum expansion and mechanical properties as well as thermal properties need to be understood to mitigate micro-annulus or cement sheath damage by operational loads, such as pressure tests, completion, thermal effects and changes in formation pressure. Finite Element simulations coupled with temperature simulations are in general required. This includes impact of repetitive mechanical and thermal loading and unloading (mechanical damage / fatigue).
- Possible generation of H<sub>2</sub>S, and potential impact on annular sealant (cement) should be clarified.

In the context of steels and alloys, there have been recent developments in the qualification of materials for a wide range of hydrogen applications, including for underground storage [251, 252]. These developments successfully carried out series of tests to qualify the fracture toughness resistance of a selection of steel grades for OCTG (Oil Country Tubular Goods) pipes, line pipes and pressure vessels in the presence of pure hydrogen gas. A first selection of steel grades for OCTG pipes in the presence of pure hydrogen gas included:

- Grade VM55W (55 ksi proprietary grade) for weldable OCTG pipes.
- Grade K55 for seamless OCTG pipes.
- Grade VM80S (80 ksi proprietary grade/L80) for seamless OCTG pipes.

These results prove that all tested materials are suitable for hydrogen services below 100 bar hydrogen pressure. Furthermore, it can be expected that these materials are also suitable for higher pressures of hydrogen considering the quite limited impact of this environmental parameter beyond approximately 50 bar based on the thorough literature review [253], however, this requires further experimental confirmation. The results are also in line with those obtained by the Hystories project [33]. L80 and K55 grades were successfully tested as part of that project using different methodologies in a more demanding corrosive environment in porous media at H<sub>2</sub> partial pressures up to 120 bar [254]. In addition to the fracture toughness tests, fatigue crack growth rate tests are currently being carried out by one supplier in order to provide a more complete understanding of the steels' fatigue behaviour to hydrogen. Other Line Pipe and OCTG grades are also currently being tested and will be progressively added to the growing portfolio of qualified materials for hydrogen applications.

### 6.2.3 Components

The key concerns for components of wells are listed below.

- **Wellheads:**
  - Leak tightness and durability of flanges and seals for hydrogen.
  - How will hydrogen storage wellheads differ from wellheads for natural gas.
- **Emergency shutdown valves (e.g., SSSV):**
  - Ensure that these are an effective seal preventing hydrogen flow / leakage. For instance, by minimizing risk of leakage with metal-to-metal seating, use of ball valves requiring no grease, and that are maintenance-free, use of metal-free grease.
  - Hydrogen may flow at much higher velocities, this may require slam testing.
- **Tubing and (production) casing:**
  - Hydrogen diffusivity through tubing material and connections (see also below).
  - Erosional velocity at wellhead and bottom-hole.
  - Size requirements, incl. ability to lower workover and monitoring tools.
- **Connections (casing, tubing):**
  - Leak tightness and durability, use of welded (for casings) vs. threaded (for tubings) connections. Use of threaded connections may require change in regulations and standards with respect to admissible leakage rate. Welding is a hardening operation under high temperatures, which may promote hydrogen accumulation, and probably also too time-consuming though for porous media because of well depth. In case of well reuse, tubings may have to be replaced in any case since the gas production tubings will probably not be compatible with hydrogen.
- **Packers:**
  - Elastomer integrity (see under materials).
  - Leak tightness.

### 6.2.4 Topics for providing guidance on and requiring further research

The topics on which guidance must be provided and that require further research in relation to wells, are listed below.

- **Design requirements for hydrogen storage wells are missing**
  - Material selection (steel types, cement types, packers/elastomers): Selection and/or development of materials for back-production of hydrogen-rich streams containing CO<sub>2</sub>, H<sub>2</sub>S and possibly saline water, what are the key differences between hydrogen and natural gas when water is co-produced with hydrogen.

- In relation to this, there is a gap in current knowledge regarding the prediction of the composition of the back-produced stream from porous media, which depends on mineralogy and depth/ temperature, presence of brine and its saturation, microbiology, duration of injection and shut-in phases, etc.
- How to determine and quantify the long-term impact of hydrogen exposure on material durability under (fast-) cyclic variations in pressure and temperature?
- Casing design, such as number of casings, fully or partially cemented, production casing vs. tubing.
- Completion design, e.g., sand screens, tubing and packer, and SSSV requirements.
- In relation to MIC, what is the impact of high partial hydrogen pressures on microbial community dynamics and corrosion rates?
- What is the impact of cyclic stresses (mechanical, thermal) in combination with exposure to (wet) hydrogen conditions on integrity of casing and cement, especially in case of re-use of legacy wells.
- Missing standards and regulations for hydrogen. For example, admissible leakage rates at LCCS (through cement and interfaces with rock and casing), through packer, through tubing connections, and ways to test this. And as other example: are the already existing well integrity standards (ISO 16530, API 1171) sufficient, e.g., for operational management of the annulus pressure?
- Assessing reuse potential of wells:
  - How to determine whether wells can be safely reused? What measurements can help in this (e.g., well tests, cement evaluation and corrosion logs)? In particular the state of the production casings, the materials used, and the interface with the cement. For example, what is the state of the installed production casing (casing material, connections)? Furthermore, the quality of the cement sheath across the caprock(s) is a critical aspect, i.e., a certain length of cement sheath has to be validated to verify this well barrier element. While these requirements exist for natural gas storage, these are not explicitly defined for hydrogen.
  - How desirable and feasible is it to reuse natural gas production (or storage) wells for hydrogen? Are diameters of casings of natural gas production wells not too small to allow sufficiently large diameter production tubings required for hydrogen to compensate for energy density difference compared to natural gas?
  - If not reused, then how to safely plug and abandon legacy wells to minimize leakage risk?
- Corrosion management via inhibitors: are the standard oil and gas inhibitors also viable for hydrogen?
- What are admissible hydrogen flow velocities in wells such that erosion of the tubing and/or casing due to back-production of solids (that can create an environment suitable for HE) is avoided?
- What are relevant test methods and suitable facilities and equipment for testing leakage rate through cements or other annular barrier materials. Can hydrogen be substituted with something else that is safer to work with?
- How to manage pressure anomalies in the annulus? When threaded connections are used, these are likely to occur over time, hence must be managed.
- Is standard equipment for measuring, monitoring, and workovers compatible with hydrogen? Examples are pressure/temperature gauges, wireline retrievable measurement tools, wireline itself, workover rigs, and seals in blow-out preventors.
- What is the impact of flow reversals and shut-in periods on thermodynamic properties of hydrogen (e.g., Joule-Thomson effect) and its flow behaviour in the near-wellbore region? Injection and production are somewhat controlled environments, but during the shut-in period, conditions might change at the reservoir level affecting flow-wetted components and subsequently production conditions especially if the same well is used for injection and withdrawal.

- For leak testing of construction components, cement, etc., it is desirable to use a gas that carries less HSE risks than hydrogen (e.g., helium, nitrogen) but is still sufficiently relevant and reasonably available for such tests. A study for this and small-scale comparison tests should be carried out if necessary.

### 6.3 Top-side facility design and engineering

An UHS facility has many components that are similar to UGS. The main top-side facility components include compressors (and drive engines), preheaters, gas treatment equipment (gas/liquid/solid separation, dehydration, purification incl. desulphurization, etc.), flowlines, pipelines, pressure equipment, and piping materials. The following sections review the state-of-art of compression and gas treatment equipment, thereby highlighting the key aspects relevant for UHS. Further topics for guidance and research are listed.

#### 6.3.1 Compressors

- For pure hydrogen compression piston (reciprocating) compressors are the state-of-the-art, and essentially available off the shelf. It is worth mentioning though that piston compressors have never been deployed at the scale required for underground hydrogen storage, posing an upscaling challenge, and that these are commonly used for continuous operation and not intermittent operation. Furthermore, operation of high pressures may require lubrication, which may lead to contamination of the hydrogen.
- While turbo (centrifugal) compressors are the standard for natural gas, for pure hydrogen duty these do not yet exist. However, several manufacturers are developing this technology, and they expect it to reach TRL 9 within the next 10 years.
- For hydrogen – natural gas blends with (very) low percentage of hydrogen (<5 – 10%), re-use of turbo (centrifugal) compressors in natural gas storage facilities might be possible at the expense of loss of efficiency, operational flexibility, and may require a change in operational (set) points.
- For offshore duty, dimensions, weight, and vibration management are important aspects to consider. A large-scale reciprocating compressor of 10 – 20 MW capacity weighs appx. 150 – 300 tons.
- Specifically, for re-used natural gas reservoirs at greater depths, such as in the North Sea region, injection pressures may have to be unusually high (>300 bar) to overcome the reservoir pressure when they are operated close to their initial pressure. This will be less of an issue for depleted reservoirs operated far below this initial pressure.
- Specifically, for re-used natural gas reservoirs with significant residual natural gas, the tail gas flow rates and composition (after separation of the hydrogen from the withdrawal stream) will probably be (highly) variable, and this will complicate compressor operation when the tail gas is to be reinjected into the reservoir. Moreover, the tail gas occurs at low pressures when using pressure swing adsorption for the gas separation as is the industry standard, which further increases the compression challenge.
- Need for powering compressor drive engines with electricity to avoid emissions (CO<sub>2</sub>, NO<sub>x</sub>).

#### 6.3.2 Gas treatment (dehydration, separation, purification)

- For dehydration, technologies include triethylene glycol, silica gel and molecular sieve adsorption, whereby the first two are currently the state-of-the-art in natural gas storage.
- For separation/purification, the technology choice depends on the composition of the withdrawn gas, which in turn strongly depends on the type of cushion gas:
  - Is it a hydrogen – natural gas blend with significant percentage of hydrogen and natural gas (and potentially other light hydrocarbons), or



- Is it a high percentage (near-pure) hydrogen mixture with low percentage of contaminants, and which contaminants are present?
- For separation/purification, available at-scale technologies are pressure swing adsorption (PSA) or thermal swing adsorption (TSA), membrane separation, or a combination of the two (for reservoirs):
  - PSA/TSA is good for producing a pure hydrogen stream (98 – 99.9%) from a stream with high (initial) hydrogen concentration. It is a multi-stage process, whereby the quality of the stream can vary, and is expensive in terms of operational costs (OPEX). Its ability to separate out H<sub>2</sub>S and CO<sub>2</sub> depends on the adsorbent. PSA does require compression of the absorbed stream though, and a large purge.
  - Membrane separation is better suited for bulk separation of streams with a lower (initial) hydrogen concentration. It is highly scalable (small-scale to large-scale), but not so good for obtaining a pure product (<98%), hence a poor choice for higher purity. It is used in refineries for removing HC's and CO<sub>2</sub> from natural gas. Membranes scale linearly with capacity and are quite sensitive to liquids and solids. Hence, these must be removed first.
  - A key difference between PSA and membrane separation is that PSA operates at high pressure, i.e., high-pressure in – high-pressure out, while membranes output at low pressures, i.e., high-pressure in – low-pressure out, thus requiring re-compression prior to re-injection into the hydrogen transport network. This complicates the use of membranes.
  - For streams with lower (initial) hydrogen concentrations, a combined membrane +PSA solution could become the preferred solution, i.e., membranes (for bulk separation) to upgrade a stream with 70 – 80% hydrogen to 90 – 95%, with PSA afterwards to further upgrade to >98% [255] for re-injection into the hydrogen transport system.
- While these technologies are available (and operational) at scale, they have never been implemented at the scale required for underground hydrogen storage, again posing an upscaling challenge similar to compression, and again are commonly used for continuous operation and not intermittent operation.
- A key challenge in the separation of gas streams from natural gas reservoirs that are re-used for hydrogen storage is what to do with the waste stream (tail gas) after separation. Assuming an incoming stream with significant amounts of hydrogen and natural gas, then ideally two streams would be produced (by combining membrane and PSA), one stream having hydrogen pipeline specifications and one stream having natural gas pipeline specifications, while the residual waste is reinjected into the reservoir (requiring dedicated injection wells). Alternatively, a coarse solid and liquid separation can be done first, with PSA afterwards, to upgrade directly to 98% or more.
- Should nitrogen be used as cushion gas, then for the incoming nitrogen – hydrogen stream membrane separation is preferred because separating nitrogen from hydrogen in PSA is not easy.
- Should CO<sub>2</sub> be used as cushion gas, then for the incoming CO<sub>2</sub> – hydrogen stream PSA is preferred because membranes work based on the gas diffusivity and gas diffusivity of CO<sub>2</sub> and hydrogen is similar.

The engineering design of the surface facilities very much depends on the operational parameters of the storage, i.e., volumetric capacity, number of cycles, required injection and withdrawal rates, and the composition of the stored gas prior to injection and after withdrawal vs. the requirements (specs) for further use. The composition of the withdrawn gas can fluctuate, which complicates the design and engineering of the gas cleaning facilities, and the waste streams from the gas separation process can be very sizeable, posing a challenge in finding suitable sinks.

### 6.3.3 Topics for providing guidance on and requiring further research:

Below The key topics are listed for which guidance must be provided and which require further research in relation to compression and gas treatment facilities.

- Establishing technologies of choice and optimized designs for large-scale (and affordable) purification (de-blending hydrogen – natural gas, removing non-hydrogen components from back-produced streams, e.g.  $H_2S$ ) to reach the required quality level, with the remark that this quality level is not yet defined in many countries (in The Netherlands, the TSO has defined a specification of 98% or more for injection into the hydrogen transport network, [255]).
- Establishing whether natural gas standard drying units can be (re-)used. Can Glycol and adsorption dryers also be used for hydrogen? What is the water content of hydrogen compared to natural gas?
- Establishing technologies of choice and optimized designs for large-scale (and affordable) compression for pure hydrogen and hydrogen – natural gas blends, as well as the potential for re-use of current UGS compressors.
- Assessing the impact of differences between UHS and UGS on surface facilities design and associated risks.
- Assessing the impact of building and operating an underground hydrogen storage facility onshore vs. offshore to understand the differentiating factors and impact on technology selection.
- Options for tail gas utilization and/or disposal. Tail gas coming out of the post-withdrawal gas cleaning process, i.e., after purification to pipeline spec, is expected to be rich in natural gas and when reusing UGS or depleted gas fields for hydrogen storage. Additional research is required on technologies to process, compress, and re-inject withdrawn streams containing combinations of hydrogen, back-produced cushion gas (methane or other), and other contaminants such as brine,  $H_2S$  and  $CO_2$ .
- Applicability of current flow metering technologies (for monitoring, and for fiscal purposes).
- PVT understanding of the gaseous streams at reservoir, in-well, and surface conditions incl. impact of the negative JT effect.
- Understanding of water content of hydrogen blends both free water and water vapor at different PT conditions.
- Intermittent operation. Most compression and gas processing technologies are used in continuous operation. The effect of intermittency on performance, reliability and fatigue of the equipment and their components is still to be determined and can impact availability and efficiency of a storage facility.

### 6.4 Operational parameters and limits

Typical operational parameters for storage of hydrogen and natural gas include the volumetric capacity, number of cycles, required injection and withdrawal rates, and the composition of the stored gas prior to injection and after withdrawal vs. the requirements (specs) for further use. In general, surface and subsurface installations should be designed to control the process and used fluids at any combination of pressure and temperature conditions to which they may be subjected to within a determined range of operating conditions. In [256, 257, 258, 259, 260] the below operational parameters are mentioned with specifies limits for certain parameters that must be adhered to.

- **Maximum operating (storage) pressure**, which is limited to avoid mechanical failure of the caprock and gas migration through the caprock. It is commonly defined as the lowest of a) the fracture pressure of the caprock; b) the pressure at which the well integrity could be affected; c) the calculated pressure resulting from the pressure in the caprock plus the threshold capillary pressure of the caprock (in case of reservoirs). A safety margin must be applied that makes allowance for the embrittlement of rocks induced by the well casing cement job, and, more specifically, for the risk of failure liable to occur at steel – cement interfaces and cement – rock interfaces – applicable to reservoirs and caverns. Additionally, the integrity of cap rocks and

cement is impacted by prolonged (years to decades) exposure to cyclic pressure variations, i.e., start-of-life and end-of-life limits must be considered.

- **Maximum (allowable) pressure change per day**, to ensure cavern integrity and stability, and in case of storage in reservoirs, avoid occurrence of induced seismicity.
- **Minimum operating (storage) pressure**, to limit cavern convergence and ensure cavern stability, thus minimizing subsidence. In case of storage in reservoirs, avoid occurrence of induced seismicity and subsidence, avoid reservoir compaction formation damage, minimize production of solids / fines, and minimize liner collapse risk.
- **Maximum (allowable) injection and withdrawal rates**, to ensure that the maximum allowable pressure change per day is not exceeded, and to limit the flow velocity in wells and pipelines such that erosion of casing and tubing are minimized.
- **Maximum (allowable) annular surface pressure**, in the context of an annular casing pressure management concept for monitoring the completion integrity, and which allows for build-up of pressure in the annuli to be vented safely.
- **Temperature of injected and withdrawn gas**, to ensure that the thermodynamic (phase change) behaviour of the gas conforms to design of wells and surface facilities and prevents, e.g., hydrate formation.
- **Quality specifications for the composition of injected and withdrawn gas**, i.e., the amount of solid, liquid, and gaseous contaminants should not exceed certain limits to ensure that they do not adversely affect the integrity and durability of materials and components of wells and surface facilities (e.g., due to corrosion), and to allow re-injection into the transportation grid.
- The facility shall have **(minimal) emissions to the environment** in accordance with the legislation and shall entail a minimal blow down strategy.
- **Noise** shall be limited as much as possible.
- In addition, any **operational limits imposed** by the regulating authority in permits.

In the next sections, key aspects to take into account in the management of wells, pipelines, and pressure and temperature to keep control of the storage system, will be further detailed.

### 6.4.1 Well management

Well management plans will be project specific, however, there are a few key features that require focus during the well design process:

- There is likely to be significant pressure and temperature cycling due to the usage type of hydrogen stores. This will impact material and component integrity in regard cyclic fatigue risk. Re-testing or re-qualification of components may be required to ensure they can function with this design consideration.
- Hydrogen has a wide range of flammable concentrations in air and lower ignition energy than natural gas, which means it can ignite more easily. Since hydrogen molecules are smaller than methane molecules, hydrogen presents a higher potential leak risk.
- Well completion tubing and production casing components and cements must be confirmed robust with respect hydrogen sealing integrity, and HE / HIC risks.
- Hydrogen-specific assessment and performance testing of well intervention equipment with respect reliable sealing integrity, rapid leak detection, and emergency well shut-down procedures must be ensured.
- A higher cyclic operating frequency requirement means well, reservoir, and facility equipment design, systems and processes must be optimised with respect injection and withdrawal turnaround times to ensure system down time is minimised.
- The storage reservoir pressure operating window parameters should be jointly developed with respect reservoir, wells and facility needs. Key reservoir and wells concerns include minimum and maximum reservoir pressure, and rate of pressure change. These must be carefully managed to

mitigate risk with respect reservoir and well integrity, reservoir management conformance, and sustainable reservoir and well deliverability.

- A higher cyclic frequency may increase risk of cyclic sand face fatigue failure, and this needs to be considered as part of an integrated sand and fines risk and management strategy at the well design stage. Sand / fines management solutions may include a combination of downhole sand control, drawdown and erosional velocity operating constraints, and surface sand / fines production detection and trend monitoring.

It should be recognized that where cushion and working gas compositions differ (e.g., carbon dioxide and hydrogen) then gas mixture ratios that may present at any given well location over lifecycle need to be carefully evaluated and risked and findings incorporated into well material selection design. Further the relative merits of dedicated single use wells versus dual cushion and working gas use needs careful integrated evaluation in regard reservoir, well, and facility impacts.

### 6.4.2 Pressure and temperature management

There are several aspects to pressure and temperature management that require consideration during the well design process:

- If the project is intending storage in a depleted oil and gas reservoir, particular emphasis should be placed on start and end of life pressure, and the change in reservoir pressure after start-up (may cause phase changes of reservoir gases or solids deposition as pressure builds up).
- Impact of the Joule – Thompson effect: hydrogen has an inversion temperature of -80 °C and thus heats up on expansion (in the well during withdrawal, and in the near-well area on injection).
- PVT behaviour of hydrogen and mixtures of hydrogen with other gases (e.g., natural gas, CO<sub>2</sub>).
- Depending on the depth of the reservoir and the possible pressure differences, heating or cooling of the gas might become necessary.
- A whole system approach needs to be taken to pressure management including modelling of the surface facilities in order to optimise design.

### 6.4.3 Pipeline management

The following aspects are important for pipeline management:

- Further regulatory clarity is needed on noise and vibration limitation on pipelines carrying hydrogen to/from the storage site and minimizing the moisture content in the stream.
- Aero-acoustic pressure pulsing in pipelines/distribution stations may be a larger issue than in oil and gas operations due to higher velocities.
- Understanding whether the pipeline network may be used as temporary storage (line packing) and is High Integrity Pressure Protection required?
- Requirements for reinforcing offshore pipelines due to lower density of hydrogen vs. natural gas.

### 6.4.4 Abandonment and plugging procedures

The following aspects are important for cavern and well abandonment:

- Secure well abandonment procedures that will ensure containment post-closure of legacy gasses and/or insolubles.
- For salt caverns managing internal pressure post abandonment such that continued cavern convergence does not lead to a situation of high overpressures that may result in loss of integrity of the (brine-filled) cavern and/or well.
- Understanding regulatory requirements for closure and post-closure.

## 6.5 Safety and monitoring concepts

In general, monitoring requirements, and hence monitoring plans, differ depending on the project phase, i.e., pre-project, during project (operational phase), and after end of project.

### 6.5.1 Pre-operational phase

In the pre-project phase, in case of storage in a depleted gas field or UGS site, it is important to obtain a baseline status of the existing wells and reservoir. Well re-use can have significant benefits to a project through cost-reduction, and in difficult-to-drill strata, reducing project risk by re-using an established well bore. However, the well is unlikely to have been designed fit for purpose for hydrogen injection. Therefore, pre-project well integrity studies will be essential to ensure that any well reuse will function adequately during the project lifecycle, or if it cannot be reused must be abandoned according to the regulations. Monitoring or baselining well status could include assessing the cement bond log, casing corrosion, pressure history and establishing barriers. Such evaluation will be dependent on local regulatory requirements.

In addition, there is a requirement to baseline reservoir status prior to injection. This will be closely linked to modelling studies discussed in Chapter 2, 3 and 4, which do identify key project risks. From such project risk analysis, a modelling plan can be devised that will allow for timely detection and intervention of any well risks that develop during the project.

In case of cavern storage, the baseline status should reflect the current situation in terms of levels of subsidence and seismicity caused by nearby subsurface activities, e.g., presence of caverns used for salt production and for storage (e.g., hydrogen, other gases, liquids). In such situations, additional monitoring measures will likely be required, this should follow from a site-specific risk assessment.

The above-mentioned subsurface-focused safety and monitoring aspects must be integrated in an overall risk management strategy and plan for the entire facility, i.e., including a thorough assessment of risks and mitigations (and relevant monitoring plan) related to the operation of the surface facilities and impact on environment (e.g., noise, emissions), health and (external) safety.

### 6.5.2 Operational phase

In the *operational phase* there are several key aspects to consider:

- Monitoring for conformance: Is the facility operating as expected, and in conformance with internal and external standards?
- Monitoring for compliance: Is the facility compliant with rules and regulations (as laid down in permit)?
- Monitoring to mitigate risks and reduce consequences of undesired events that may occur in the facility at the surface and in the subsurface, in particular hydrogen leakage, (induced) seismicity, and subsidence.

To understand these, a suite of monitoring tools is likely to be required, focusing on leakage (integrity of wells, reservoir, caverns), subsidence and seismicity (geomechanical stability of cavern and reservoir). These requirements will be closely linked to the regulations, and understanding /definition of acceptable leakage rates, and levels of subsidence and seismicity.

In-well monitoring of well integrity is likely to include:

- Inflow and outflow performance monitoring, including for risks such as sands/solids clogging the inflow.
- Annuli monitoring of pressure and gas composition.
- Corrosion and erosion monitoring of the casing, tubing and affected well architecture.
- General integrity tests such as functionality of the SSSV.

- Barrier monitoring.

These can be complemented by distributed monitoring systems covering:

- Ground movement (seismicity) and deformation (subsidence).
- Subsurface flow of reservoir fluids (e.g., hydrogen / natural gas working gas, hydrogen / natural gas / CO<sub>2</sub> cushion gas).

It is important to note that the installation of monitoring devices affects well and completion design, i.e., the need to be able to deploy the required tools through the tubing or casing (without and with tubing installed – e.g., monitoring cables, chemical injection lines) in the correct part of the well that might affect size selection. Furthermore, the installation of in-well tools might impact well integrity when cable throughput through barriers (e.g., packer) is required, hence should be assessed. Finally, the validity for hydrogen storage of existing procedures and instructions which are applicable for natural gas storage (or other commodity) must be assessed. If found to be invalid, then procedures may have to be adjusted and/or new technical solutions may have to be developed.

### 6.5.3 *Post-operational phase*

In the post-operational phase it is important to evaluate barrier integrity, this is normal procedure for well abandonment. Naturally, the well should be designed with (ultimately) abandonment in mind, i.e., the barrier philosophy should take into account the safeguarding of the integrity of the well in the post-abandonment phase. It is not yet established whether post-closure monitoring will be required, however, given that hydrogen is a valuable resource it is likely that the reservoir will be depleted prior to closure, reducing leakage risk. However, if CO<sub>2</sub> is used as a cushion gas, ongoing monitoring may be required to verify lack of leakage.

### 6.5.4 *Topics for providing guidance on and requiring further research*

Below are listed the topics that guidance must be provided on and that require further research in relation to safety and monitoring of hydrogen storage, whereby in the case of reservoirs, the complexity of storing mixtures of gases (e.g., hydrogen, natural gas and CO<sub>2</sub>) should be taken into account:

- Gas tightness testing and evaluation of the last cemented casing shoe.
- In-well monitoring (conformance & containment): what technologies are available and where are developments needed?
- Availability of measuring tools that are applicable in a hydrogen and natural gas and/or CO<sub>2</sub> environment.
- Assessment of acceptable leakage rates in combination with measurability.
- Gas quality monitoring and leakage detection: quality monitoring (e.g., in the cavern or reservoir, near-well) and leakage detection (e.g., in and around the wells and site).
- Monitoring microbiological and chemical processes in the well, cavern, and reservoir. Bio- and geochemical processes can have a critical influence on hydrogen purity, therefore such monitoring systems will be of high importance.
- Reservoir brine monitoring: To establish reservoir conditions which may cause a risk to the well/cement integrity.
- Odorizing of hydrogen, i.e., hydrogen is an odorless gas, and for safety reasons, adding an odorant helps detection by smell, similar to odorized natural gas.
- Lack of regulation and guidelines for hydrogen-specific well design and monitoring.

## 6.6 **Impacts on development and operations**

In the next sections, a number of key risks related to wells and facilities, and their impact on operations will be highlighted, in particular technical, safety, and economic. Please note that this list is non-



exhaustive. A generic overview of potential hazards and adverse effects is included in Table A-1 in Appendix A. It is recommended to conducting a full bow-tie analysis of the risks of storing hydrogen in the subsurface.

### 6.6.1 Technical risks and impacts

The following technical risks may impact operations, with the remark that while labelled as technical, the fact that they lead to leakage of hydrogen also poses safety risks (see next section):

- Unacceptable leak rate through annular sealant (e.g., packer) requiring suspension of operation.
- Unacceptable leak rate through micro-annulus between annular sealant and pipe or formation requiring suspension of operation.
- Damage to annular cement by post-cementing operations, causing leakage, and requiring remediation.
- Annular sealant chemical alteration by hydrogen exposure, change in properties, loss of sealing ability.
- Issues with equipment during well intervention, and associated rig requirements.

### 6.6.2 Safety risks and impacts

As an industrial gas, hydrogen has been produced, transported, stored, and used for decades, and the risk and safety aspects are well-known. For UHS, the “new” focus areas include wells treatment (material selection, impact of cycling, workovers, monitoring) and hydrogen-specific risks in surface facilities. Each different hydrogen project will have its own risks. However, key themes are leakage, fire, explosion, and toxicity (with respect to impurities in the hydrogen stream). In relation to the effects of leakage of hydrogen (and associated gases, fluids), the position where the leakage occurs is important:

- Leakage can occur **below ground**, from the reservoir (into surrounding rocks, and upward into overburden towards surface), or from the well (e.g., into annulus and upward to wellhead), causing environmental pollution (groundwater).
- Leakage can occur **at the surface**, at the wellhead or in surface facilities, potentially leading to fire or explosion, with high risk of harming life (humans, animals), and causing environmental pollution, noise, intense light. Special attention must be paid to places at or near the well where hydrogen can accumulate and form an explosive cloud. Some operators need to build a housing around their wells in order to reduce sound emissions, which needs monitoring to prevent hazardous situations.

### 6.6.3 Economic risks and impacts

The list below highlights a number of economic risks that may impact operations:

- Very limited practical experience with hydrogen storage in reservoirs (no commercial sites yet and very few pilots) with risk of unexpected “surprises” and not-optimal solutions will lead to higher costs.
- In case of leakage, cost of repair and downtime can be (very) significant. For example, excessive cost of suitable annular sealant, placement equipment and methods, and long waiting time for sealant to cure.
- Cost of land: processing facilities for UHS may require larger footprint leading to higher costs.
- Investment in cushion gas (hydrogen is expensive, alternatives may be much cheaper).
- Investment in upgrade of facilities (e.g., more wells) in case existing UGS could not deliver the required amounts of gas (energy), implying additional costs.

## 6.7 Summary and findings and recommendations

This chapter provides an overview of the current state-of-the-art regarding the application and required modification of well designs, surface facilities components and monitoring/safety concepts for UHS. While many future UHS projects are expected to rely on new wells and facility components, there are also sites which foresee the repurposing and modification of existing UGS facilities and legacy oil/gas wells. UHS operators and regulatory authorities will generally need to know why, when and how to differentiate from the established design, safety and monitoring concepts/standards that are currently applied in oil and gas production and natural gas storage operations. For UGS operators it will be helpful to know what modifications are needed to repurpose wells and facilities and which components can be safely re-used with hydrogen.

Functional requirements and designs for hydrogen storage wells and top-side facilities are largely similar to those for natural gas storage. Research efforts mainly focus on reviewing, modifying, testing and verifying individual component designs and materials used prior to their application in UHS context. Safety and monitoring concepts need to be established for the project phases before, during and after operations. Following key actions are identified from this review:

### Reviewing existing facilities, concepts and standards (operators, researchers):

- Identify recommended mechanical properties, expansion, etc. for annular sealants, and use this to determine well geometry such as hole size, pipe size and pipe wall thickness. Investigate the potential impact of well materials subjected to hydrogen and back-produced reservoir by-products (CO<sub>2</sub>, H<sub>2</sub>S, brine, etc). More specifically a better understanding is required for elastomers, cement with gas retaining additives, and for steel connection tightness and welds susceptibility to HE.
- Further research is needed on the impacts of microbial induced corrosion, wellhead material selection, and the application of corrosion inhibitors for hydrogen. Operators can play a crucial role in providing materials from abandoned wells or facilities in order to assess and define the criteria for re-use in UHS.
- Identify relevant (laboratory) test methods and suitable facilities and equipment for testing leakage rate through cements or other annular barrier materials, and cement/sealant to pipe and formation interface (micro-annulus issues).
- Evaluate the applicability of alternative cushion gases (e.g., CO<sub>2</sub>, N<sub>2</sub>). Assess the consequences for the storage project, e.g., in terms of overall performance, required separation equipment, safety standards, and costs (capital investments and operational costs).

### Development of new concepts and implement modifications (operators, researchers):

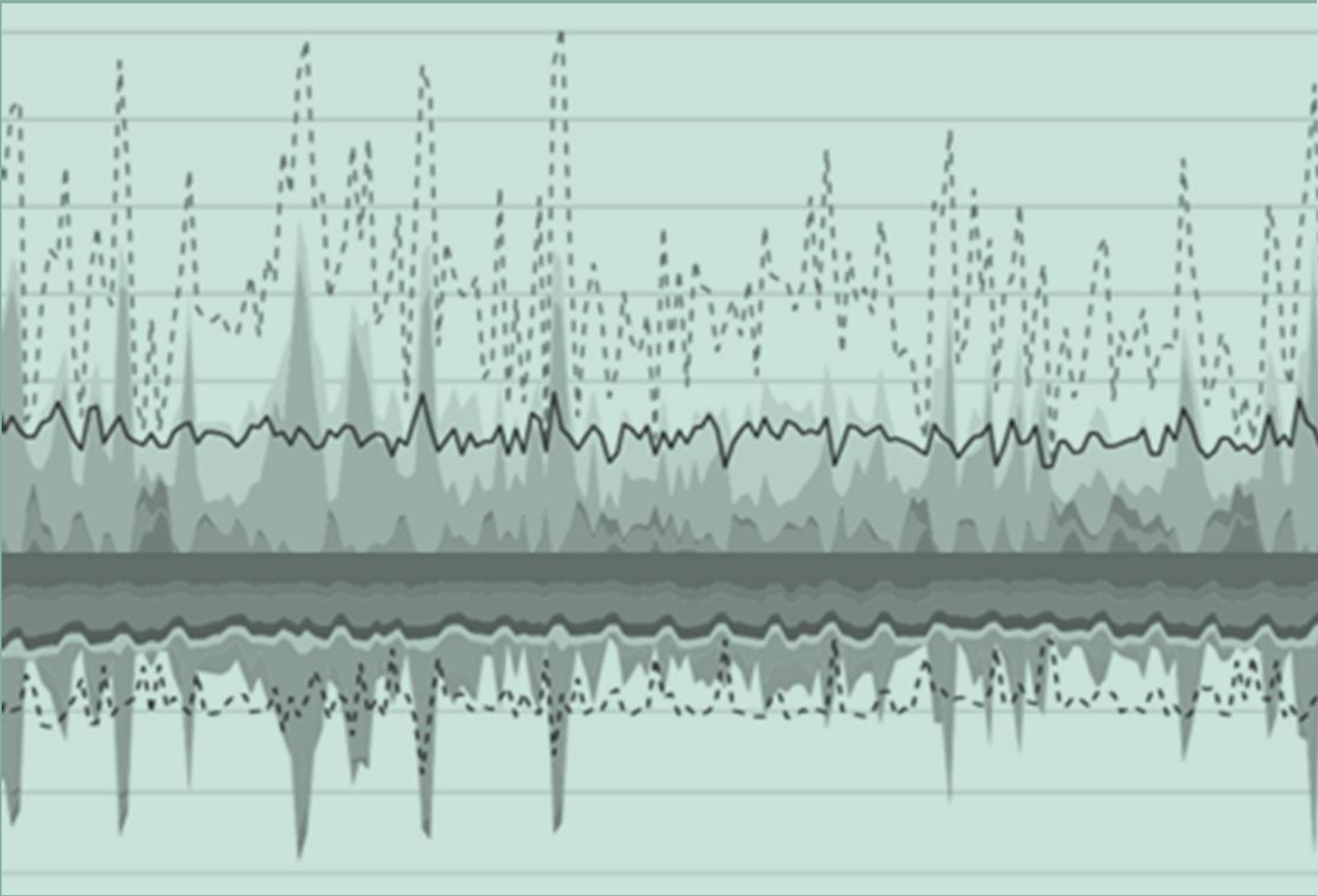
- Develop super-low permeability cements in case cement(s) currently used are found to be incapable to act as a barrier to hydrogen flow and be susceptible to hydrogen impacts. Develop alternate materials and coatings for the casing of (legacy) wells that are to be repurposed for UHS, and where there the installation of a new tubing is not an option.
- Establish optimal well placement, well completion and well functionality concepts for different types of reservoirs (architecture and geological characteristics) and operational parameters.
- Develop strategies to deal with changes in operating conditions at the reservoir level during shut-in on the flow-wetted components, especially if the same well is used for injection and production.
- Provide solutions to upscaling compression and gas treatment solutions, which, so far, have not been applied at the required scale. This includes the techno-economic optimization challenge regarding gas processing to reach the desired purity

**Testing and verification (operators, authorities, researchers):**

- Agree on a model to determine potential damage to cement sheath. Develop specific monitoring technologies and strategies, e.g., in-situ embrittlement monitoring, alternate self-healing coatings, extended fibre or alternate "similar" technology that provides fibre benefits.
- Develop test methods, equipment, and media (for example alternatives to hydrogen) for evaluating cements or alternative sealants, and define acceptance criteria for such tests.
- Improve prediction of possible changes in the composition of the gas stream withdrawn from the reservoir and develop/modify purification components and concepts that are able to deal with potentially varying gas qualities.

# CHAPTER 7

## Economics and Cost Estimations



Projections of demand and business case impacts

Cost estimation of new underground hydrogen storages

Towards a cost estimation model for underground hydrogen storage

Comparison of different public capital expenditure estimations

## 7 Economics and cost estimations

### 7.1 General introduction

Chapter 5 provides an overview of published studies which have investigated, screened and assessed the technical and geological potential for underground hydrogen storage at national and transnational scales. Most of these studies are conducted at a rather high and theoretical level and do not consider the effort and costs required to develop these sites and establish the facilities to meet required performance. Such costs will largely determine the economic viability of storage sites and reservoirs, which will result in a further limitation of the practical and even effective storage capacity, and which is typically presented by studies evaluating regional underground storage potential. Still, it is likely that sufficient sites meet the expected storage demand. A site-specific UHS cost estimation for 800+ porous media traps, 21 bedded salt deposits and salt domes throughout Europe is proposed in [240].

The similarities between UGS and UHS among others concern the type of geological reservoirs used for storage (porous formations, salt caverns and lined hard rock caverns), storage operations, facility design concepts, site monitoring, life cycle analysis, analysis of economic feasibility, spatial planning and various social aspects. Despite these similarities there are also some major differences that mainly have an origin in the physical and chemical properties of the hydrogen gas being stored (see Chapters 2 – 4) and impact the screening criteria of suitable sites (Chapter 5) as well as the design of storage facilities and wells (Chapter 6).

This chapter provides a brief overview of the potential consequences of these changes to the cost of development and operation (respectively, CAPEX and OPEX). Recommendations are given towards assessing potential business models for hydrogen in different settings, optimizing cost-effectiveness of UHS development and reducing investment risks.

### 7.2 Projections of demand and business case impacts

Table B-1 in Appendix B present the locations and examples where several decades of experience has been obtained with the commercial operation of town gas storage (mixtures of ca. 50% hydrogen and other gases) in porous reservoirs and storage of pure (up to 95%) in salt caverns. The deployment of UHS at larger scale – in particular for pure hydrogen – with the objective of contributing to net-zero emission energy systems, however, requires overcoming many technical, economic and social barriers.

The development of a cost-effective and efficient method of deploying underground hydrogen storage is one of the current key focuses of industry and scientists. Such demand arises to satisfy the prospects for a rapid implementation of this technology as the projections of hydrogen production and end-uses predict a six to seven-fold increase between now and 2050 [2, 3]. Although expected storage demand towards 2050 is still quite uncertain, it is expected that the required volumes are comparable to or even surpassing the current operational volumes for UGS. The following potential limitations and barriers for the generation of viable business cases related to UHS technology are identified.

#### Purity requirement for Hydrogen grids

Gas quality specifications for hydrogen injection in transport pipelines may have an impact on the business cases because of costs associated with purification. This may impact depleted fields more than salt caverns.

#### Immature market for hydrogen storage

At present, the demand for large-scale storage of pure hydrogen is not yet established. While this demand is expected to emerge in the coming 10 – 20 years, the projections and expected areas of application are still highly uncertain. Consequently, there is no clear insight in what the future business

case for UHS will look like and how the return on investments will evolve. This keeps investors from making long-term investment decisions and causes further delays in developing viable business cases. Furthermore, the influence of the type of market regulation (regulated access vs. third-party access) on UHS development should be assessed.

### **Lack of experience in UHS operations**

As mentioned above, the experiences with pure hydrogen storage are limited to a few cases of salt cavern storage only. While these sites are dedicated to securing feedstock supply for local petrochemical industry [18, 261], there is no experience with commercial operation and implementation of business cases in a hydrogen-based energy system.

### **Availability and knowledge of appropriate geological structures**

The screening and ranking of feasible geological reservoirs are still in an early phase (Chapter 5). The validation of site selection criteria is subject to further research and demonstration and the geological play for UHS is largely immature. The selection and maturation of sites may require substantial investments for exploration, appraisal, sampling and testing. Furthermore, there is an uneven distribution of salt deposits, hydrocarbon reservoirs, and aquifers, which may limit the scope for developing viable business cases.

### **Geochemical and microbiological impacts**

Currently there are substantial knowledge gaps regarding the prediction and quantification of impacts from geochemical interactions between hydrogen, rock matrix and brine as well as from microbial consumption of hydrogen (Chapter 2). These impacts may lead to a deterioration of storage performance, contamination of hydrogen, loss of hydrogen in the reservoir, corrosion of wells, and possible safety issues at the surface. Consequently, these effects may lead to higher costs and uncertainties with regards to the effective operation of storage and generation of revenues.

### **Cushion gas requirements**

The injection of cushion gas (Chapter 4 and 6) is a significant part of the total CAPEX of a storage site. While hydrogen is very expensive, future research could assess the opportunity of employing alternative gases as cushion gas [90]. This would reduce the overall cost of hydrogen storage, improving the related economics and fostering new possible business scenarios. On the other hand, the use of an alternative cushion gas could impose additional costs for purification and lead to a loss of injected hydrogen as mixing takes place at the cushion gas – working gas interface.

### **Compatibility with existing infrastructure**

UHS sites may reuse existing infrastructure elements (e.g., platforms, pipelines, wells) depending on whether these elements are fit for repurposing (Chapter 6). If such infrastructure must be developed from scratch, then this may have a major impact on the CAPEX. Furthermore, the TRLs of equipment and individual facility components for UHS (e.g., compressors, purification) may not be mature enough.

### **Legal aspects and social perception and acceptance**

With a growing international interest, hydrogen is already included into several EU policies and legal acts, and it is expected that this will be introduced in many further initiatives. Regulations, policies and standardizations for UHS (e.g., permitting, planning, visions on upscaling, market development, norms and definitions) still lack formal definitions in the present legal and economic framework and still need to be established at a level that is required to embed the current technical advances in the social context (Chapter 8). As a result, investors for UHS are confronted with uncertainties regarding their license to operate and realizing the expected return-on-investment on the long term. Further uncertainties may result from a lack of public and/or political acceptance and support, poor stakeholder involvement.



### 7.3 Cost estimation of new underground hydrogen storages

An underground storage site is not an off-the-shelf manufactured product. Most notably, it has very site-specific requirements and is heavily dependent on the usage and functions that determine the required specifications.

As other geology-related activities, underground hydrogen storages depend on the geological conditions that are found. The depth of the storage has large impact on the storage cost. The fact that it is onshore or offshore would have even larger impact, should offshore hydrogen storage develop (offshore storages did not develop for other gaseous or liquid hydrocarbon products, except a handful of exceptions). A non-exhaustive list of site-specific parameters that have a large impact on the project costs for storage are:

- For salt caverns: the depth, the thickness of the salt layer and its insoluble content, the opportunity to have leaching water available (distance to sea or surface water), the opportunity of brine disposal or re-use (valorisation of the brine in chemical industries, possibility of injection in a deep aquifer, of emission in the sea, brine pipeline distance).
- For porous media: the depth, the level of characterization of the trap (especially for aquifers, heavy site investigation campaigns can be required, and lead to many investigated sites not being selected), the presence of abandoned wells requiring interventions including plugging (especially in case of depleted fields), the reservoir injectivity and number of wells required to be drilled.

In addition, underground storage sites are cycle-specific: for a given storage capacity, sites being able to inject in 1 week or in 3 months play different roles in the energy systems, provide different types of value and have different capital and operational costs. Above ground facilities especially (compressors, dehydration, separation units) would be very different. Subsurface facilities may as well be affected, for example by the number of wells required for a porous media storage. Another issue relates to the regulatory required purity rate in the hydrogen transport network. In case of porous media, impurities should be separated from the produced hydrogen and higher required purities results in higher separations costs. Cost estimations are therefore hardly generic as these relate to each particular design. Such figures are hardly accurate when used to for estimating the cost of another project. Cost comparison should therefore be considered very carefully, as many factors can result in large cost variations. One of the main sources of uncertainty stems from the fact that while the capacity (usually in Nm<sup>3</sup> of hydrogen, tons or MWh) is usually taken as the reference cost unit, the withdrawal and injection capacities are not.

The following sections provide a qualitative evaluation of CAPEX, OPEX and maintenance cost elements.

## 7.3.1 CAPEX Elements

## Pre-feasibility and Screening

Cost element: Regional G&G studies	
<b>Objective:</b>	Screen and rank geological leads, assess geological play characteristics defining technical suitability such as reservoir, seal, geochemistry, etc. Relies on existing and accessible data from prior subsurface exploration and deployment activities.
<b>Relevance:</b>	Optional, yet quite essential in early stages of UHS technology development and geological play definition. Most efforts are expected for aquifers where prior exploration data is typically limited or absent and complexity/uncertainty is still high. Depleted gas fields often have extensive datasets from exploration and drilling activities while dynamic behaviour and reservoir characteristics are known from production. On the other hand, they might have abandoned wells whose tightness has to be assessed. Salt formations are often already well known in Europe and for onshore locations – especially those that are already exploited for salt mining and storage – the geological suitability may be more predictable. Offshore salt structures are known from geological mapping, but they are rarely explored or exploited. Still, these structure may eventually be considered for cavern construction and UHS at some point, e.g., in case of lacking social support for onshore development.
<b>Challenges:</b>	Although the general concept of regional G&G reconnaissance and site screening is a widely and commonly applied practice, there are still essential knowledge gaps regarding the exact criteria that determine the suitability of porous rock formations. Often, the available data may lack specific measurements, samples and analyses that are key to assessing UHS-specific aspects such as geochemical composition, proxies for microbial activity, and tightness to hydrogen flow.
<b>Cost impact:</b>	Low, there are no major risks of being confronted with unexpected and excessive expenditures. The situation is however quite different for aquifers, that requires more exploration to characterize the trap, than for depleted fields and salt deposits.

Cost element: Business case assessment	
<b>Objective:</b>	Determine storage demand, market, revenue models, possible connections to energy system, spatial planning options, required production rates, options for subsidy, risk mitigation options, etc.
<b>Relevance:</b>	Essential for all storage types. Business case criteria and parameters may be different however.
<b>Challenges:</b>	UHS is still precommercial and the market for large-scale hydrogen storage has not developed yet. There is a lack of practical experience on how to generate revenues in the future hydrogen economy.
<b>Cost impact:</b>	Low to moderate, generally there are no major risks of being confronted with unexpected and excessive expenditures in assessing a business case. Any decisions resulting from a business case assessment may lead to substantial investments and associated investment risks in the next phases. Moreover, when a business case assessment reveals high unexpected and expensive costs and substantial extra investments for a project development, then the project might never reach the next phase. Parties may decide to stop the project when the business case is not expected to be feasible.

## Phase: Exploration and Front-End-Engineering-Design

<i>Cost element: Obtain exploration permits and licenses</i>	
<i>Objective:</i>	Typical and crucial requirement in most jurisdictions which provides the sole right to evaluate, drill and test prospects in a given area.
<i>Relevance:</i>	Essential for all storage types. Some licenses may be bound to existing production licenses (e.g., depleted gas fields, concessions for salt solution mining)
<i>Challenges:</i>	Licensing and permitting procedures may not yet be fully adapted to the UHS in current regulatory frameworks. Responsible authorities may lack essential expertise specific to UHS license aspects. This may result in longer permitting and licensing procedures.
<i>Cost impact:</i>	Low, there are no major risks of being confronted with unexpected and excessive expenditures. Initially the costs of permitting and licensing may be higher while regulatory frameworks have not fully been established and experiences are gained.

<i>Cost Element: Geological maturation of site</i>	
<i>Objective:</i>	Further studies that assess all essential characteristics of the selected site, including analyses to determine and validate the geological feasibility to deploy UHS and implement the expected business case. The outcomes form the basis for investment decisions to drill (optional) exploration or appraisal wells, while the final results will be used to decide on further engineering and construction of the UHS facilities.
<i>Relevance:</i>	Essential for all storage types. Type and extent of analyses will differ substantially between salt caverns and porous formations.
<i>Challenges:</i>	Similar to other activities such as oil and gas, geothermal, CO <sub>2</sub> storage and UGS. The type of exploration data needed to validate UHS suitability vs other types of subsurface activities may be different, however. Existing data sets of depleted fields whilst typically offering lots of reservoir and production data usually lack detailed data in regard the overburden and underburden.
<i>Cost impact:</i>	Low to moderate depending on how much information will be available from previous exploration and development activities, and the local setting and complexity. There are no major risks of being confronted with unexpected and excessive expenditures. The maturation must finally lead to an acceptable degree of risk reduction to allow further investment decisions towards the project construction and operational phases.

<i>Cost Element: Geophysical surveying</i>	
<i>Objective:</i>	Acquire new geophysical data from, e.g., 2D/3D seismic surveys, gravitational surveys, electromagnetic surveys, etc. These data are typically integrated to define, map and model a storage reservoir, structural traps, faults, etc.
<i>Relevance:</i>	Optional, yet quite essential if no data is available to provide a continuous 3D image of the site that is targeted for storage.
<i>Challenges:</i>	These are conventional techniques that are well known and established in other exploration and production activities (oil, gas, geothermal). No specific needs for application in UHS evaluations.
<i>Cost impact:</i>	Typically low. There may be some risks of ending up with higher-than-expected costs. High quality geophysical data can be crucial for further reduction of investment risks, understanding operational challenges and preventing risks (e.g., faults).

<b>Cost Element: Exploration and appraisal drilling</b>	
<b>Objective:</b>	Drill new wells, take samples and measurements, and perform well tests which are needed to prove suitable conditions for underground storage of hydrogen and to define operational parameters.
<b>Relevance:</b>	Essential for UHS in aquifers. Optional for UHS in depleted gas fields and salt formations without existing caverns. Generally, not needed for existing salt caverns or gas fields that are already deployed for UGS.
<b>Challenges:</b>	Drilling is similar to other activities such as oil and gas, geothermal, CO <sub>2</sub> storage, and UGS. The testing and sampling requirements may be different however for UHS. Some of these tests are still in a research phase.
<b>Cost impact:</b>	Potentially high when one or more exploration and/or appraisal wells must be drilled. The costs of wells are site-specific (e.g., determined by depth, offshore vs onshore, complexity, types of samples and measurements involved). Depending on the availability of prior information, there may be significant risks of running into higher-than expected costs (e.g., loss of well, failing to detect a suitable reservoir). The information obtained from exploration drilling is crucial for further risk reduction and investment decisions in the project construction and operational phases.

<b>Cost element: Front-End-Engineering-Design (FEED)</b>	
<b>Objective:</b>	FEED focuses on technical requirements and identifying main costs for a proposed project and is used as the basis for the construction of facilities, drilling and completion of injection wells, connection the facilities to transport pipelines, etc. FEED also addresses executional requirements (e.g., contracts, permits, licenses) and specifications of expected operational parameters to reflect the project-specific client needs. It depends on a good understanding of the prime asset (reservoir) development, optimised conceptual use in the hydrogen context in regard of cushion / working gas (type, timing, transition from any existing configuration or use, enhanced natural gas recovery integration, abandonment engineering, well type, placement, number) and facility support requirements to optimise the reservoir storage asset. A good FEED will avoid significant changes during the execution phase. This action usually takes around 1 year to complete for larger-sized projects.
<b>Relevance:</b>	Essential for any subsurface development that includes engineering aspects
<b>Challenges:</b>	Many specifications in a FEED procedure for UHS are still under research and subject to experimental testing, prototyping and demonstration.
<b>Cost impact:</b>	Low to moderate. The costs of a FEED procedure are typically well defined and there are no major risks of running into unexpected and excessive expenditures. Cost impacts from a FEED procedure are very dependent on the technical requirement (e.g., ensure zero emissions for CO <sub>2</sub> , NO <sub>x</sub> , H <sub>2</sub> , etc.). These requirements must be included in the design and may lead to required solutions with high costs.

<b>Cost element: Baseline monitoring</b>	
<b>Objective:</b>	Obtain a comprehensive insight in the environmental situation prior to construction and development, which is used as a reference for further monitoring and design of preventive and mitigative measures.
<b>Relevance:</b>	This is a typical requirement for most subsurface activities including UHS, yet the extent, scope and requirements of the baseline monitoring program may differ per jurisdiction, type of storage technology and local setting.
<b>Challenges:</b>	There are still substantial knowledge gaps with regards to the potential effects of UHS on the environment in case of incidental losses and other hazards. This is also relevant for the design of baseline monitoring programs
<b>Cost impact:</b>	Typically low, there are no major risks of running into unexpected and excessive expenditures.

**Phase: Construction**

<i>Cost element: Drilling and completion of injection and production wells</i>	
<i>Objective:</i>	Planning, placement and completion of all required injection/production wells according to the FEED and storage plan.
<i>Relevance:</i>	The number of injection and production wells may significantly differ for each UHS option. New salt caverns are already equipped with at least one well used for leaching, and which may be required additional completion for injection/production of H <sub>2</sub> . Sometimes a second well is drilled for UHS. A depleted gas field or saline aquifer may require multiple wells to operate UHS. The number depends on the contracted injection/production rates as well as the size, complexity, characteristics of the reservoir, and current depletion levels which may be challenging for drilling operations if reservoir pressures are very low. Legacy wells may be suitable but often lack the required specifications (e.g., diameter, placement, completion)
<i>Challenges:</i>	There is still substantial research needed to fully understand hydrogen flow/recovery of porous reservoirs and what is the optimal well placement and development for UHS operations. In that respect an optimal balance must be found between investment costs and project performance.
<i>Cost impact:</i>	Typically high. The risk of being confronted with unexpected and excessive expenditures is still there (e.g., issues during drilling, loss of a well) yet much smaller than for a virgin reservoir where much less information is available.

<i>Cost element: Building the surface facilities for compression, gas treatment and pipeline connection</i>	
<i>Objective:</i>	Constructing all facilities needed to operate the UHS site according to agreed project specifications. This element can be further subdivided into the following main elements: 1) connections to the hydrogen transport grid, 2) compression units, 3) well head connection points for injection and production, 4) gas drying units, 5) hydrogen purification units (especially challenging for porous reservoirs), 6) metering, 7) power supply.
<i>Relevance:</i>	Essential for all UHS options. The number and capacity of compressors will differ based on the contracted injection rates, operational pressure ranges, etc. Purification units are specifically needed for UHS in porous reservoirs. Requirements for purity from pipeline specifications and from end-users will also impact the design and costs.
<i>Challenges:</i>	There is a lot of experience from UGS developments. Some facility components will require adaptations to become suitable for working with hydrogen. These are still being developed and tested. Additional costs may arise from safety precaution measures (e.g., monitoring equipment, blow-out and explosion prevention, dealing with corrosive reaction by-products)
<i>Cost impact:</i>	High. A proper FEED specification will help to avoid unexpected costs and delays during construction

<b>Cost element: Cavern leaching including evacuation/disposal of brine</b>	
<b>Objective:</b>	Salt caverns must be leached first according to agreed design criteria before being used for UHS. The extracted brine must be evacuated to either a salt production facility (not part of the UHS CAPEX) or a pipeline system for brine disposal. The latter may require additional processing and cleaning of the brine in order to comply to environmental criteria for disposal.
<b>Relevance:</b>	Only relevant for salt formations where new caverns must be leached
<b>Challenges:</b>	Little. The design and procedures for leaching storage caverns are well known and technically very mature. These are not different from, e.g., UGS caverns.
<b>Cost impact:</b>	Moderate. The costs may be much lower when connection to existing leaching and salt production facilities. In that case there may also be revenues from selling salt products. The total cost of leaching can be high when large cavern clusters are needed. However, the cost per cavern will probably be lower as the CAPEX for leaching facilities is divided over more caverns. There may be unexpected costs due to issues encountered during leaching. Such issues are however quite rare and well managed given the high maturity and existing good mining practices.

<b>Cost element: Filling cushion gas</b>	
<b>Objective:</b>	A storage reservoir must have a minimum pressure to enable operations and contracted production rates. In the case of UHS in salt caverns there will be a minimum pressure to prevent the convergence of the cavern under lithostatic pressure. Such convergence could lead to subsidence at the surface and loss of storage volume in the cavern. Ideally the cushion gas resembles the gas being used for storage (in this case hydrogen). Different cushion gases are also being considered to lower the cost.
<b>Relevance:</b>	Essential for all types of storage. UHS in porous formations is often characterized by higher cushion gas – working gas ratios than UHS in salt caverns.
<b>Challenges:</b>	Hydrogen is very expensive and may be converted by geochemical and microbial processes when residing in the reservoir for multiple years (especially with porous reservoirs). Therefore, other types of cushion gas are being investigated. The applicability and consequences are still subject to research and demonstration before having confidence on the applicability. A (probably relatively small) amount of the cushion gas may disappear due to conversion, leakage away from the actual working volume and possibly residual trapping of hydrogen (particularly for aquifers). This means that additional gas has to be injected over time to maintain the same working volumes and pressures.
<b>Cost impact:</b>	Very high. Cushion gas (particularly hydrogen) is often regarded as the largest cost factor in UHS development. This will vary with the evolution of the price of hydrogen over time, the type of development and the agreed storage performances. The risk of unexpected costs due to cushion gas may result from volatile and poorly predictable price developments.

### 7.3.2 OPEX elements

<b>Cost element: Injection (compression, hydrogen pre-processing)</b>	
<b>Objective:</b>	Establishing the required pressures and specifications for injecting hydrogen into the reservoir at agreed rates. The costs involve the energy that is being used to compress the hydrogen
<b>Relevance:</b>	Essential for all UHS options
<b>Challenges:</b>	No significant challenges expected
<b>Cost impact:</b>	Moderate to high. This is the main cost for operating the UHS facility. there are no major risks of having unexpected and excessive expenditures



<b>Cost element: Extraction (drying, purification, separation)</b>	
<b>Objective:</b>	Processing hydrogen extracted from the hydrogen and bringing it on spec according to the grid and/or end-user requirements. The costs will involve the energy and additional resources carry out the gas treatment.
<b>Relevance:</b>	Drying will be essential for all UHS options. Cost for purification may be significantly higher for UHS in porous reservoirs than in salt caverns
<b>Challenges:</b>	The returned hydrogen from the reservoir may contain specific (corrosive) impurities which require specific attention and safety measures.
<b>Cost impact:</b>	Moderate. No major risks of having unexpected and excessive expenditures are expected

<b>Cost element: Monitoring</b>	
<b>Objective:</b>	Regulatory requirements may enforce certain monitoring activities to timely detect and mitigate safety and environmental hazards. Monitoring may furthermore be used to manage and optimize operations and effectiveness of storage.
<b>Relevance:</b>	Optional for all UHS options (may be mandatory by certain regulations)
<b>Challenges:</b>	There is still a need for developing monitoring tools and methods to assess the behaviour of hydrogen in the subsurface
<b>Cost impact:</b>	Low

### 7.3.3 Maintenance cost elements

<b>Cost element: Facility and well maintenance and workovers</b>	
<b>Objective:</b>	Ensuring a safe and effective operation of all facility components including wells and reservoir. This is done by regular and incidental maintenance, repair and workovers
<b>Relevance:</b>	Essential for all UHS options. In the case of UHS in salt caverns, there may be a need to regularly scan and re-leach the cavern.
<b>Challenges:</b>	There are still uncertainties regarding the impacts and potential maintenance/repair needs when running UHS under fast cycling loading conditions.
<b>Cost impact:</b>	Potentially high when there is a long downtime for repairs or when workovers require extensive efforts and repairs

<b>Cost element: Mitigation of subsidence impacts and/or induced seismicity</b>	
<b>Objective:</b>	Under various jurisdictions, operators are responsible for mitigating environmental impacts due to subsidence and/or induced seismicity. Adaptation to subsidence may be related to water management, adapting critical infrastructure that is sensitive to it, etc.
<b>Relevance:</b>	Typically associated with UHS in salt caverns which may induce subsidence due to salt creep and cavern convergence. In some case, UHS in depleted fields or aquifers can raise induced seismicity risk due to pore pressure change affecting the fault system.
<b>Challenges:</b>	Subsidence in the project lifetime may be limited. Yet substantial subsidence may take place over longer time periods after cease of operations.
<b>Cost impact:</b>	Potentially high when there are dense cavern clusters and UHS caverns are being developed in areas sensitive to subsidence impacts.

## 7.4 Towards a cost estimation model for underground hydrogen storage

The Hystories project [33] has recently proposed a conceptual design [262] meant to be representative of new typical UHS facilities that could be built in Europe. It sets detailed design parameters that can then enable a project-based cost estimation. It also presents a cost estimation model [87] that is

applied to this conceptual design. A proper definition of the design and project-based cost estimate approach enables to:

- Have clear boundary limits and a reference design.
- Be hydrogen-specific, whereas estimates based on analogues (“expert opinion”) are not.
- Keep several parameters as tuneable ones:
  - Parameters that are not known with certainty yet, including:
    - Material cost factor: the choice of Carbon or Stainless steel being not fully standardized yet.
    - The part of hydrogen that would not be recovered due to geochemical reactions, microbiological activity or hydrodynamic processes, especially for porous storages (likely also site-specific).
  - Parameters that are site-specific, including:
    - Depth (and operating pressures).
    - Hydrogen network operating pressure.
    - Number of production and operation wells for porous media.
    - Number and volume of salt caverns.
    - Cushion gas to Total gas ratio.
    - Parameters that are cycle-specific, including the Withdrawal to injection capacity ratio.

This enables distinguishing costs associated to the Withdrawal deliverability (€/MW) from those related to the storage capacity (€/MWh), as presented in Table 7-1. The main items that are quoted are listed in Table 7-2.

*Table 7-1: Orders of magnitude of an underground storage from [87], based on the Conceptual Designs defined in report [262]: a 250 MM Sm<sup>3</sup> capacity site for salt caverns (21.000 tons; 0.7 TWh LHV) and a 550 MM Sm<sup>3</sup> capacity for porous media (46.000 tons, 1.5 TWh LHV).*

*\* Subsurface CAPEX rate per storage volume capacity is highly dependent on the number of wells required to reach storage target performance. Costs are a function of depth, etc. See details in [87] and [262]*

*\*\* Surface CAPEX rate per withdrawal flowrate capacity is highly dependent on the purification unit requirements and on the installed compression power (ratio WTIR).*

*\*\*\* (Subsurface-related fixed OPEX to be cumulated to surface-related fixed OPEX*

Cost rate	Unit	Salt caverns	Porous media
Subsurface CAPEX Rate (per working gas capacity)	EUR per KWh <sub>H2</sub> (LHV) [Range]*	0.51 [0.44 – 0.69]	0.20 [0.11 – 0.45]
Surface CAPEX Rate (per withdrawal flowrate max. capacity)	EUR per KW <sub>H2</sub> (LHV)	205	645**
Variable OPEX rate (per cycled quantity, and for COE = 60 EUR/MWh)	EUR per MWh <sub>H2</sub> (LHV)	2.25	3.83
Fixed OPEX rate*** (% of related CAPEX / year)	% Surface CAPEX / year	3.7%	3.7%
	% Subsurface CAPEX / year	0.4%	1.5%

Table 7-2: Main Capital costs incurred during UHS. A cost estimation formula is given for each in [87].

Activity	Salt cavern	Porous media
Site development	Development, drilling, leaching completion	Development drilling
	Leaching plant	First gas fill
	Leaching operation and maintenance	
	De-brining and first gas fill	
	Cushion gas	
	Contingencies for subsurface facilities	
Surface facilities	Material selection	
	Hydrogen process plant	
	Well pad, downstream equipment and piping	
	Interconnection between wellheads and gas plant	
		Hydrogen purification
	Balance of Plant	
	Contingencies	

### 7.5 Comparison of different public capital expenditure estimations

Several other sources have published cost estimations of underground hydrogen storage. If CAPEX is generally published, fixed and variable OPEX, and abandonment costs are generally not. The comparison below will therefore be limited to CAPEX.

Table 7-3 and Table 7-4 present the comparison of the main public references of UHS CAPEX that have been found. These two tables show the huge variability of the public cost estimations that can be found in the literature. This variability. It can partly be explained by the basis of design that was assumed. For instance, HyUnder [35] considers a very large depleted gas field and probably assumes its conversions essentially requires very few additional wells. On the contrary, the aquifer and depleted field costs given in [214] are high, especially when considering these are costs of a (US dollar) price-level of 2014. Further it is probably also related to the fact that the basis of designs they used are built to have the same working gas capacity as their salt cavern case (a relatively small salt cavern). These depleted field and aquifer cases are therefore very small for porous storages.

Last, it is noted that only the Hystories project chose to distinguish costs that are related the storage capacity (€/kWh) and those related to the deliverability of the storage (€/kWh). This enables adaptation of the cost estimates for different cycles. Surprisingly, they find the same overall cost of 20€/kg for the Basis of design used in their cost estimate, despite a very different cost structure.

The fact that these public sources used different basis of designs, the reference year/country or currency, however, do not explain why these costs figures are sometimes more than one order of magnitude different. The explanation also largely comes from the fact that the boundary limits of the cost estimate are not the same and not exclusive from other influences, as presented in Table 7-5 and Table 7-6.

Table 7-3: Public cost estimates of underground hydrogen storage in salt caverns. Note that the exchange rate 1\$ = 1€ is considered, and that no discount rate is applied. Sources used: Hystories 2022 [87], HyUnder 2013 [35], ENTEC 2022 [263], Lord et al. 2014 [214], DNV 2019 [264], Ahluwalia et al. 2019 [265].

Item	Unit	Hystories 2022	HyUnder 2013	ENTEC 2022	Lord et al. 2014	DNV 2019	Ahluwalia et al. 2019
<b>Costs</b>							
CAPEX /energy	€/kWh	0.51	0.17	0.20	0.20	0.65	1.1
CAPEX /power	€/kW	205					
Total CAPEX for the Basis of design	€/kgH <sub>2</sub>	20	6	7	7	22	36
	€/Nm <sup>3</sup>	1.8	0.5	0.6	0.6	2.0	3.2
	€/kWh	0.6	0.17	0.20	0.20	0.65	1.1
<b>Basis of design (main)</b>							
Cavern gas vol.	m <sup>3</sup>	8 x 380,000	500,000	no detail	580,000	no detail	80,000
LCSS depth	m	1,000	1,000		1,158		800
Hydrogen wvol.	tons H <sub>2</sub>	8 x 2,635	4,000		1,912		500
Withdrawal to injection ratio	-	2.0	1.0		1.7		Assumed 1
Withdrawal cap.	ton H <sub>2</sub> /day	8 x 23	259		118		50

Table 7-4: Public cost estimates of underground hydrogen storage in depleted fields and aquifers. Note that the exchange rate 1\$ = 1€ is considered, and that no discount rate is applied. Sources used: Hystories 2022 [87], HyUnder 2013 [35], Lord et al. 2014 [214], DNV 2019 [264].

Item	Unit	Hystories 2022 Aquifer or depl.field	HyUnder 2013 Rehden depl. field	Lord et al. 2014 Aquifer or depl. field	DNV 2019 Aquifer	DNV 2019 Depl.field
<b>Costs</b>						
CAPEX /energy	€/kWh	0.20	0.03	0.42	0.25	0.11
CAPEX /power	€/kW	645				
Total CAPEX for the Basis of design	€/kgH <sub>2</sub>	20	1,0	14	8	4
	€/Nm <sup>3</sup>	1.8	0.09	1.3	0.8	0.3
	€/kWh	0.6	0.03	0.42	0.25	0.11
<b>Basis of design (main)</b>						
Number of wells	-	8 operation + 24 observation	16 extra operation wells	1 operation well	no detail	
Depth	m	1,200	1,500	1,403		
Hydrogen wvol.	tons H <sub>2</sub>	46,000	312,800	1,912		
Withdrawal to injection ratio	-	2.0	1.7	1		
Withdrawal cap.	ton H <sub>2</sub> /day	403	5,177	60		

Table 7-5: Boundary limits of the public cost estimates of underground hydrogen storage in salt caverns. Sources used: Hystories 2022 [87], HyUnder 2013 [35], ENTEC 2022 [263], Lord et al. 2014 [214], DNV 2019 [264], Ahluwalia et al. 2019 [265].

Item	Hystories 2022	HyUnder 2013	ENTEC 2022	Lord et al. 2014	DNV 2019	Ahluwalia et al. 2019
Exploration	no	yes («exploration»)	assumed not	no	assumed not	yes («geological survey»)
Leaching plant	yes	no	assumed not	yes	assumed not	assumed not
Cavern Construction (drilling, leaching, MIT, 1 <sup>st</sup> fill)	yes	yes	yes	yes	yes	yes
Cushion gas	yes	no	yes	yes	yes	assumed
Above ground facilities (compression and drying)	yes	no	no	yes	assumed not	yes
Brine disposal	yes, pumps + 30 km pipeline	no	assumed not	assumed not	assumed not	10 miles pipeline + injection well
Engineering Management Services	yes	yes	assumed	assumed	assumed	assumed
Contingencies	yes	assumed	assumed	assumed	assumed	assumed
Owner costs	no	no	assumed not	no	assumed not	assumed not

Table 7-6: Boundary limits of the public cost estimates of underground hydrogen storage in aquifer and depleted field. Sources used: Hystories 2022 [87], HyUnder 2013 [35], Lord et al. 2014 [214], DNV 2019 [264].

Item	Hystories 2022	HyUnder 2013	Lord et al. 2014	DNV 2019
<b>Exploration</b>	no	assumed not	no	assumed not
<b>Underground storage developments (wells)</b>	yes	assumed additional wells only	yes	assumed
<b>Cushion gas</b>	yes	yes	yes	yes
<b>Above ground facilities (compression and drying)</b>	yes	assumed not	yes	assumed not
<b>Gas treatment</b>	yes (but very hypothetical)	assumed not	assumed not	assumed not
<b>Engineering Management Services</b>	yes	assumed	assumed	assumed
<b>Contingences</b>	yes	assumed	assumed	assumed
<b>Owner cost</b>	no	no	no	assumed not

It is not always clear whether the above ground facilities of a storage site are included or not in the estimation. And if they are, what is the deliverability they are able to provide.

From the above two tables, it is noted that the boundary limits greatly differ from one source to another. Most notably, the cost of above ground facilities is not always included, despite it being larger than the subsurface costs in many cases.

Using public figures for cost estimates of UHS is not straightforward and can hardly be applied without a very good knowledge and understanding of the design of the project. Every underground storage cost estimate is site-specific. In [240], the authors apply the cost model of [87] to 800+ porous media traps and to the most relevant salt structures in Europe, providing a high-level view of the variability of the cost of developing underground storage sites.

## 7.6 Summary of findings and recommendations

### Reliability of cost estimates

With current knowledge fairly reliable CAPEX and OPEX estimates can be determined for UHS in salt caverns, as these are comparable to other mature underground storages in salt caverns. For UHS in porous reservoirs the uncertainty of cost estimation is still substantial, notably due to gas treatment and other measures and solutions that are needed to mitigate impurities in the hydrogen extracted from the storage reservoir.

In order to further increase the reliability of cost estimates, following actions are required:

- As project development costs are highly site-specific and new sites require substantial exploration and maturation efforts, it is recommended to identify and establish mechanisms to support such assessments towards most promising sites to reduce uncertainties and investment risks early on in the project.
- Further efforts are needed to identify and demonstrate gas treatment requirements and strategies for UHS in porous reservoirs.
- R&D, technical developments and demonstrations are needed to support the development of hydrogen storage in Lined Rock Caverns.

### Determination of UHS demand and system values

Several countries and regions have established estimates of expected UHS demand between 2030 and 2050. Many of these, including European Level UHS demand are based on a set of hypotheses that are still uncertain. There is a limited foresight in how the UHS market will develop. At the same time, the deployment of UHS infrastructure at expected scale will take decades, which means that demonstration and development must start as soon as possible.

The following actions are required to prepare and support conditions for a timely and responsible development of UHS:

- Assess criticality UHS for security of energy supply (national and European). Such assessments should not only regard the minimization of the cost of Net-zero energy systems but also take into account externalities such as supply disturbances, geopolitical developments, and global hydrogen market developments.
- Validate a reference deployment scenario of the underground hydrogen storage (and transportation) infrastructures.

### Development of market conditions

As of today, there is no market that supports commercialisation and upscaling of UHS. There are emerging insights in the key services and storage strategies that can be supplied by UHS. The valorisation schemes are not yet in place, however.

The following actions are required to close the key market gaps for UHS between now and 2050:



- Assess market conditions / possible frames for generating long term revenues.
- Determine reasonable state-regulated prices/revenues for UHS.
- Establish market regulation framework/conditions, especially for early development projects (to be performed in close cooperation with policy makers at national and EU level). This includes the influence of regulated access vs. third-party access models on UHS development.

### **Finding the optimum storage and withdrawal capacity for different roles (max system benefits minus UHS costs)**

Underground storage of hydrogen can provide fast cyclic and seasonal cycles solutions. In order to enable a minimum cost for the overall energy system, optimal ways must be found to deploy underground hydrogen storage in combination with other forms of flexibility (interconnectivity, demand response, curtailment) and energy storage (batteries, compressed air, pumped hydro, heat storage, etc.). In addition, the cost of developing UHS is highly site dependent. The optimum use of UHS will aim at identifying the optimum storage and withdrawal capacity, and also account for the high site-dependence of UHS development cost.

# CHAPTER 8

## Societal Embeddedness of Underground Hydrogen Storage



Towards technical and societal maturation and development

Implementation of societal embeddedness level for underground hydrogen storage

Progressing maturity of underground hydrogen storage projects

## 8 Societal embeddedness of underground hydrogen storage

### 8.1 General introduction

The successful implementation of underground hydrogen storage (UHS) relies on the level of maturity of the applied technology (technical readiness level/TRL) but will also strongly depend on the social license to operate. The prerequisites for such a social license (e.g., implementation of environmental impact analyses, formalized stakeholder responsibilities, public engagement procedures, clear policies and regulations, an open and self-regulating market) may not be in the scope of the typical technology maturation cycle [266]. These are, however, as crucial to the successful implementation of an UHS project, as is the demonstration of technological feasibility. This chapter introduces a generic framework and guidelines that support the identification, evaluation and implementation of prerequisites that are relevant for enabling the societal embedding of UHS as the technology progresses through the stages of conceptualization, prototyping, demonstration and commercialization.

#### 8.1.1 Scoping

The following prerequisites are initially defined to address the societal embedding for UHS implementation and upscaling:

- Spatial planning and project development
  - Identification and evaluation of the societal aspects of UHS site selection in relation to techno-economic criteria.
  - Guidelines to assess and classify the environmental, legal and societal maturity of UHS projects throughout the techno-economic project life cycle, and how to implement these insights in existing resource classification frameworks (this report briefly discusses various of these frameworks in Section 8.2.3).
- Regulation
  - Identification of legal and regulatory framework elements for licensing, permitting and oversight of UHS projects.
  - Assessment of the interlinkage between policy development and the establishment of the regulatory framework.
- Safety
  - Identification of risks, recommended practices for risk management, monitoring and mitigation of potential impacts and safety risks to the human, natural and built environment.
  - Communication of risks and impacts to stakeholders and public including an understanding of associated uncertainties.
- Society
  - Generic considerations for policy support, public engagement and stakeholder involvement early in the process of technology maturation and project development.
  - Support societal embedding via public information sharing, education and stakeholder involvement.
  - Implementation of authority driven processes, where authorities granting allowances for building a storage facility have an obligation to distribute information and make the approval process as transparent to stakeholders as possible.

Identification and pro-active engagement of external stakeholders by the project developer is essential early in the project, and in alignment with the planning stages [266, 267]. Mechanisms for soliciting, discussing and incorporating feedback from stakeholders and local communities such as open and frequent meetings, information events and site visits with stakeholders and public should

be part of a continuous process throughout the entire project life cycle, from conception through to abandonment. Such interactions may provide room for the communication of public and other stakeholder concerns, identification of benefits, education, fact-finding and evaluation of alternative technological solutions.

Projects cannot easily progress without a clear legal and regulatory framework. On one hand, responsible authorities need these frameworks to govern permitting and licensing procedures and to supervise responsible development and operations. On the other hand, operators depend on a stable and predictable regulatory framework to justify large investment costs and long lead times associated with UHS project development, in order to ensure viable conditions for storage operations, which may last for several decades. Having a constructive dialog with regulators would identify any areas of concern or gaps that might require clarification at the appropriate legislative level. Although often confrontational, a cordial attitude between UHS project representatives and regulators builds trust and efficiency in project execution. Similar experiences and practices from several early CCS projects, in which regulations were co-developed with the projects, may be captured and used as a starting point for the UHS context.

The safe and responsible operation of an underground gas storage site can depend on how effectively communication is managed with first responders, the public, and other regulatory and supervisory bodies that may share jurisdiction and responsibility in a project, as well as its technical design, operation and monitoring requirements. Transparent communications and clear procedures between a project and its stakeholders have been shown to be a critical element in understanding and identifying safety aspects for local communities, infrastructure and environment and thereby to increase trust. First responders and governmental organizations need to train regularly together with operator personnel on how to act in case of an accident. Therefore, confidence by regulators and the public in a project not only depends on the assurance that adequate and up-to-date measures are taken to reduce risks and prevent accidents, but will also depend on the precautions taken to prevent damage and mitigate impacts. Such principles form the basis for typical bow-tie analyses (see among others [268, 269]).

Because an UHS facility would exist and operate within a dynamic societal context, it can be affected among other by changes in public support, updated regulations, new policies, and the way projects are covered by media. Proactive approaches including education and public outreach over the life of the facility can facilitate continued operation during times of change. A facility may become better established within a community through transparent communications, public engagement and development of shared ownership.

The four areas mentioned in this section are part of a more comprehensive framework, which assesses the progressing levels of societal embeddedness of emerging technologies. This framework will be introduced and discussed in Sections 8.2 and 8.3.

### *8.1.2 Relationship between technical and societal aspects in UHS*

Much of the technical work (e.g., site-characterization, drilling of wells, building of storage facilities) that will be required for UHS site screening and deployment is largely insensitive to the location, language, and culture associated with the project site. The technical performance, safety measures, monitoring requirements and societal acceptance, however, depend on local geological, geographical and cultural characteristics, which may be vastly different. And while it is possible to define general trends for societal embedding, the dependence on locally varying sociological parameters potentially results in different acceptance levels at different locations.

Most of the geological, technical and economic challenges addressed in Chapters 2 – 7 will also affect the social aspects. Table 8-1 below provides several examples.

Table 8-1: Examples of interdependencies between technical and social aspects.

Geological aspect	Possible relations to social aspects (examples)
<b>Microbial and geochemical impacts</b>	Site assessment and development need to anticipate potential impacts of biotic and abiotic reactions on hydrogen including measures to ensure safe operation and identifying and mitigating impacts of corrosive and toxic reaction products (e.g., H <sub>2</sub> S).
	Regulations will be needed with regards to site assessment and development, quality assurance of hydrogen returned from storage, the monitoring of reaction by-products and the processing of hydrogen.
	Informing stakeholders and local communities on potential hazards specific to UHS and the plans to mitigate their consequences.
<b>Storage integrity</b>	Regulations regarding safe operating limits, monitoring and mitigation of hazards such as induced seismicity, subsidence and leakages.
	Informing society and first-responders on mitigative measures in case leakage accidents occur.
	Business and use cases, capital expenditures, hydrogen deliverability, and project economics depend on the reservoir's operational characteristics.
	Inform public on possible societal benefits and costs of UHS including alternatives that are realistically available for a given site or for UHS in general.
<b>Facilities and wells</b>	Linkages with the development, management and operation of H <sub>2</sub> transportation and distribution systems.
	Footprint and impacts of UHS infrastructure on the natural and built environments including land and sea use, nature protection areas, environmental quality, proximity to residential areas.
	Policies regarding the development and lay-out of future energy systems.
	Compliance with regulations regarding methane or gas emissions, maintenance and inspection schedules.

Technological and societal aspects of UHS may be drawn from experience with oil and gas production [234], underground storage of other gases such as CO<sub>2</sub> [24], natural gas [139] and compressed air [270], several of which have a long track record of safe and economical operation [271]. As a result, existing academic curricula, industrial recruitment and training programs, workflows in operating and service companies, and regulations [272] could potentially be applied to UHS, with changes specific to the properties of hydrogen gas [273].

It is widely recognized that human factors ("soft skills") can influence a project's success (e.g., [274, 275, 276]). For example, [277] identified geological and reservoir constraints, technical and safety imitations, legal barriers, conflicts of interest, and social acceptance of underground hydrogen storage that could be barriers to UHS implementation. Societal aspects have the potential to make or break a project, depending on the nature and degree of engagement of stakeholders external to the project team itself. The degree of two-way dialog and agreement that is achieved at all stages of a project's life-cycle with citizens, communities, governmental officials at all levels, regulators, and social and traditional media outlets can be influential factors for the success of the project, independent of its technical maturity or safety record.

There are various examples for different types of technology development, in which the social attitude has been impacted by changing societal developments. Two are given below:

- Coal-fired power plants that were previously considered to be harmful to the environment have become increasingly relied upon in certain parts of the world as an additional energy source during times of restricted supplies of natural gas or renewable energy.

- The Netherlands comprises a huge onshore geological and technical potential for underground storage of CO<sub>2</sub>. While a CCS project was considered in an onshore depleted gas field in the Barendrecht area (near Rotterdam), the public debate resulted in a political ban on developing storage of CO<sub>2</sub> in onshore subsurface formations [278, 279]. At present regulations in the Netherlands consider CCS projects in the Dutch offshore only.

## 8.2 Towards technical and social maturation and development

### 8.2.1 Introduction

Over its life cycle, a storage project involves many steps and decision gates, which range from the selection and validation of a suitable storage site up to the decommissioning, abandonment and after care of sites once storage operations have ceased (Figure 8-1). These steps and decisions typically depend on milestones and conditions that must be fulfilled by local geological, technical, economic, legal, regulatory, environmental and social characteristics before a subsequent phase can start.

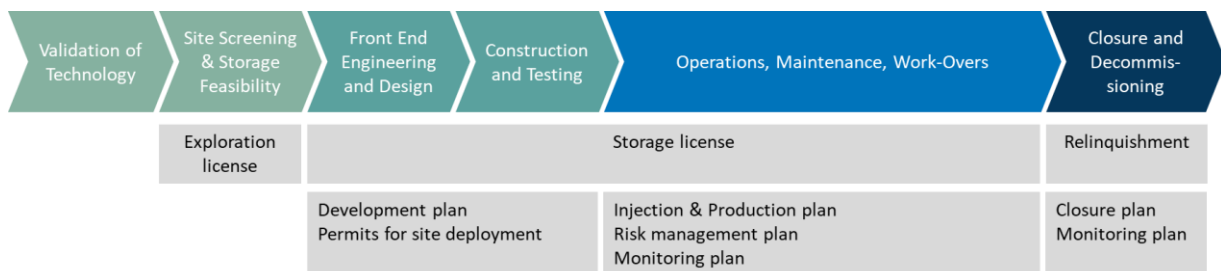


Figure 8-1: Typical life cycle of an underground storage project.

For a storage technology to be matured, developed and operated, it must satisfy two interdependent sets of definition and evaluation, namely:

- 1) **The definition of the generic technical and social milestones and conditions that must be fulfilled.** The technical and economic conditions typically result from generic research and innovation stages including conceptualization, experimental validation and ultimately the full-scale demonstration in various relevant environments to be deployed. The social conditions typically encompass legal terms, regulations, norms for safety and environmental impacts, knowledge requirements, stakeholders' responsibilities, platforms for social engagement and market needs and are typically defined and determined by regional or national governmental institutions with the help of relevant stakeholders and societal organizations.
- 2) **The assessment of the local site characteristics which need to be validated against the defined milestones and conditions.** This level typically relates to the actual development of a storage project at a specific site. In order to mature, develop and operate this project, the conditions and milestones as specified in 1) must be established. For example, the project can only be successfully deployed when the viable geological conditions and technical designs are known (at generic level) and can be tested against the local geological setting. And in order to grant a permit for development of the project, a license framework must be in place, formal authorities must be appointed and permitting requirements must be known.

Chapters 2 – 7 focus on the identification and assessment of the generic technical and geological conditions that must be met in order to develop and operate an UHS project. The insights and experiences obtained from laboratory research, modelling, prototype testing and demonstration determine how close UHS will be to a point that allows technically viable and commercial development and operation. The advancement of the technology can be measured according to the Technical Readiness Level framework (see Chapter 1).



The following sections will first introduce the *Societal Embeddedness Level* framework which establishes and evaluates the social milestones and conditions that should apply to UHS development (see point 1 above) and the associated *Technical Readiness Level* framework, which establishes the viable technical conditions through the research – demonstration – development chain. Subsequently project readiness schemes are discussed, which focus on the implementation of technical, economic and social conditions in a local project setting (see point 2 above).

### 8.2.2 Societal Embeddedness Level

The Societal Embeddedness Level (SEL) approach [266, 267] was developed as a means to systematically assess and establish societal considerations while a technology progresses from conceptualization towards demonstration and commercialization. In [267] it is mentioned that a lacking or incomplete societal embedding due to public resistance, absence of appropriate policy and regulations, unsolid business cases and uncertainty concerning the impact on the environment may result in a slow-down or even failure of the commercialization and upscaling of the technology, even if it is technically validated and ready for deployment. In their paper they present examples where CCS demonstration projects have been cancelled due to an immature regulatory framework and lack of permitting procedures.

Technology Readiness Level  
(IEA-scale)

Mature	11	Proof of stability reached Predictable growth
Early adoption	10	Integration needed at scale Solution is commercial and competitive but needs further integration efforts
	9	Commercial operation in relevant environment Solution is commercially available, needs evolutionary improvement to stay competitive
Demonstration	8	First of a kind commercial Commercial demonstration, full scale deployment in final form
	7	Pre-commercial demonstration Solution working in expected conditions
Large prototype	6	Full prototype at scale Prototype proven at scale in conditions to be deployed
	5	Large prototype Components proven in conditions to be deployed
Small prototype	4	Early prototype Prototype proven in test conditions
Concept	3	Concept needs validation Solution needs to be prototyped and applied
	2	Application formulated Concept and application of solution have been formulated
	1	Initial idea Basic principles have been defined

Societal Embeddedness Level  
(Sprenkeling et al. 2022)

5*	Upscaling and maintenance Societal aspects adapted to evolutionary changes in system and social environment
4	Deployment Innovation proven in societal environment
3	Demonstration Social aspects included in system
2	Development Social aspects assessed
1	Exploration Social aspects explored



Figure 8-2: Correspondences proposed between Technology Readiness – TRL (after [25]) and Societal Embeddedness – SEL (after [267]).

The SEL framework provides guidance to start establishing the social aspects that are needed for demonstration, commercialization and upscaling already in the early stages of technology research and development. Social aspects and conditions are expected to be identified and explored during the conceptualization phase while further assessment and implementation happens as the technology is validated by experimental testing and ultimately full-scale demonstration. Consequently, the SEL levels are correlated with the TRL framework (Figure 8-2). The purpose of SEL is to determine and put

in place the instruments (e.g., permitting procedures) and conditions (e.g., safety norms) which are needed for a local storage project to mature in the social context.

The SEL framework defines a 2D matrix (Figure 8-3) with four social dimensions on the horizontal axis (i.e., impact on environment, stakeholder involvement, policy and regulations, market and financial resources) and four progressive levels of maturation on the vertical axis (i.e., exploration, development, demonstration and deployment). Each node in the matrix is characterized by certain milestones that need to be achieved in order to reach the next level in the respective social dimension.

	SEL 1: Exploration	SEL 2: Development	SEL 3: Demonstration	SEL 4: Deployment
<b>Dimension 1: impact on the environment</b>	Milestones	Milestones	Milestones	Milestones
<b>Dimension 2: stakeholder involvement</b>	Milestones	Milestones	Milestones	Milestones
<b>Dimension 3: policy and regulations</b>	Milestones	Milestones	Milestones	Milestones
<b>Dimension 4: market and financial resources</b>	Milestones	Milestones	Milestones	Milestones

Figure 8-3: Dimensions and levels of SEL, from [267].

Below the four social dimensions and the expectations for each level are briefly summarized (after [267]). This chapter furthermore proposes a 5<sup>th</sup> level, which addresses the need for keeping the societal aspects in mind as the environment changes. This may be due to new societal needs, technical improvements or new competing technologies, societal responses to impacts or new insights concerning impacts, new experiences on how to mitigate impacts, changing political climate and policy goals, and changing market conditions. Section 8.3 will further focus on the specification and implementation of the SEL milestones.

Level 1: Social aspects explored	
<b>Dimension 1:</b>	The natural, built and social (human) environment is identified and the potential impact the innovation concept can have on this environment is explored. There is a close relationship to technical aspects, as these will typically determine the magnitude of effects, hazards and risks, but also with thresholds and norms that need to be considered.
<b>Dimension 2:</b>	Insight in societal attitude is gained and a basic inventory of all stakeholders in the field is made, which is augmented in level two. Important aspects among others are public perception and social acceptance, stakeholder communication and engagement concerns and uncertainty about risks, and trust. New developments in the technical domain result in a need for education and transparent information. Stakeholders will be confronted with these new technical aspects, which will impact their work and result in a need for a common language and understanding. Stakeholders and the public will be engaged depending on their level of expertise. On the public side, there should be transparent information about the pros and cons of the technology from an early (pre-development) stage onwards.
<b>Dimension 3:</b>	The current political climate and context is explored, as well as existing policies and regulatory frameworks concerning innovations. This relates to interaction with different levels of government, the jurisdiction and primacy, establishment of funding, political support, the understanding of the political landscape and the regulatory framework. As technology development gains momentum there may be a need for roadmaps and visions on how the technology will be upscaled and to what ends.
<b>Dimension 4:</b>	A market need/gap is identified. Such gap or need may be connected to funding requirements and schemes (public and private), the availability of resources, assessment of costs and benefits and the evaluation of a market base.

Level 2: Social aspects assessed	
<b>Dimension 1:</b>	The impact the technology can have on the environment is assessed and the environment of the whole technological system (i.e., the interaction of all individual components that define the storage site and the subsurface reservoir) is explored, where after the potential impact the whole technological system can have on the environment is explored.
<b>Dimension 2:</b>	The level of participation of the stakeholders in the development phase is agreed to, as well as a design for stakeholder participation, tailored to the current phase of technology development. Additionally, the public opinion towards the technology is assessed and possible trust building measures are identified.
<b>Dimension 3:</b>	Current policies and regulatory frameworks are reviewed, and potential enabling aspects and barriers in the regulatory framework are identified.
<b>Dimension 4:</b>	The market need/gap analysis and evaluation is performed in combination with the establishment of an initial business case proposal. This includes the need of conducting a feasibility study.

Level 3: Social aspects included in the system	
<b>Dimension 1:</b>	Any negative impacts that are identified in Level 1 and 2, have been addressed by adequate procedures to prevent and mitigate these before, during and after development and operations.
<b>Dimension 2:</b>	A stakeholder inventory for the system is set up and a design for stakeholder participation is made for the demonstration of the technology and its system. Current public feedback and concerns are incorporated into the project design and (further) outreach campaigns are initiated in order to increase public reassurance.
<b>Dimension 3:</b>	The assessment of policies and the regulatory framework is repeated for the technologies' system, and regulatory and policy frameworks support the demonstration of the technology and its system.
<b>Dimension 4:</b>	The business case is adapted to findings for the demonstration phase and the technology, and its system are adapted to market and customer needs.

Level 4: Innovation proven in the societal environment	
<b>Dimension 1:</b>	Negative impacts of the technology and its system that have emerged from the demonstration phase are mitigated, and harm to the environment is as low as possible within the limits of the project/technology
<b>Dimension 2:</b>	The stakeholder participation is adapted to the deployment of the technology and its system, and the deployment of the technology and its system is supported by sufficient relevant stakeholders and the public.
<b>Dimension 3:</b>	Regulatory barriers are overcome and supporting policies, laws and regulations are in place for the technology and its system.
<b>Dimension 4:</b>	The market is ready for adoption of the technology and its system, and the technology and its system meet market and customer needs

### 8.2.3 Project readiness schemes

In this chapter the term “readiness level” was applied in a broad sense to encompass both geologic and engineering (“technological”) aspects of a potential UHS project. For example, an early stage an UHS project would involve the identification of potential candidate sites, including an assessment of their geological settings (e.g., bedded or domal salt, favourable sedimentary sequences), general lithostratigraphic suitability for hydrogen storage (e.g., reservoir and caprock), locations of potential sources and consumers of hydrogen, and simple volumetric calculations (e.g., [234, 241, 280]).

The SPE Storage Resources Management System (SRMS) [281] has been developed as an adaptation of the widely applied Petroleum Resources Management System. The SRMS specifically focuses on underground storage of CO<sub>2</sub>. Here the storage resource is defined as the quantity (mass or volume) of CO<sub>2</sub> that can be stored in a given geologic formation. The system framework resource assessments estimate total storable quantities in known and yet-to-be-discovered (i.e., identified) geologic formations. Commercially viable projects are classed as “Capacity” (equivalent to “Reserves” in PRMS) whereas unproven or potentially commercial discovered storage are classed as “Prospective” or “Contingent” storage resources, respectively if the projects are not commercial. For the classification “Capacity” to be assigned, SRMS requires the project to be ‘commercial’, which implies that the project is economic and all societal, regulatory and environmental criteria are met. However, the SRMS framework does not specify these criteria (which are often locally defined) or set out any recommendations or how to satisfy them.

The Storage Readiness Level (SRL, [234]) framework details the maturity stages during early prospect definition and exploration and extends towards the stage in which a project is operational and on injection. SRL also considers early involvement of country jurisdictions and stakeholders by the fact that they are responsible for initiating regional and national storage assessments. Involvement of relevant authorities comes into view as licenses and permits must be issued for exploratory drilling and appraisal, including provision of required risk and environmental impact assessments. The SRL approach considers that criteria for societal embedding are in place (i.e., criteria and procedures for environmental impact assessment, regulatory framework, stakeholder engagement, financial schemes, etc.).

Like SRMS, the United Nations Framework Classification for Resources – UNFC-2019 [282] is a resource project-based and principles-based classification system using three main categories or axes (Figure 8-4) determining the environmental – socio – economic viability (E-axis), the technical feasibility (F-axis) and the level of confidence of (to be developed) quantities (G-axis) of projects.

The E-axis (Figure 8-4) designates the degree of favourability of environmental – socio – economic conditions in establishing the viability of the project, including consideration of market prices and relevant legal, regulatory, social, environmental and contractual conditions. The E-axis in this chapter was found to be correlated to the dimensions of the SEL framework. The second set (the F-axis) designates the maturity of technology, studies and commitments necessary to implement the project. These projects range from early conceptual studies through to a fully developed project that is producing and reflecting standard value chain management principles. The F-axis is correlated to the TRL framework. The third set of categories (the G-axis) designates the degree of confidence in the estimate of the quantities of products from the project. TRL and SEL do not determine quantities as these frameworks are not designed to classify specific projects. The quantities are, however, correlated with those defined in SRMS. The environmental – socio – economic viability (E), technical feasibility (F), and degree of confidence in the estimate (G) each have different levels represented as classes and subclasses using a numerical coding system. Combinations of these criteria create a three-dimensional system (Figure 8-4).

The above project classification frameworks do not specifically prescribe which social, environmental, economic, regulatory criteria must be met, or which reference levels are considered as benchmarks. Unlike technical norms, these criteria are locally or culturally defined.

## UNFC Categories and Examples of Classes

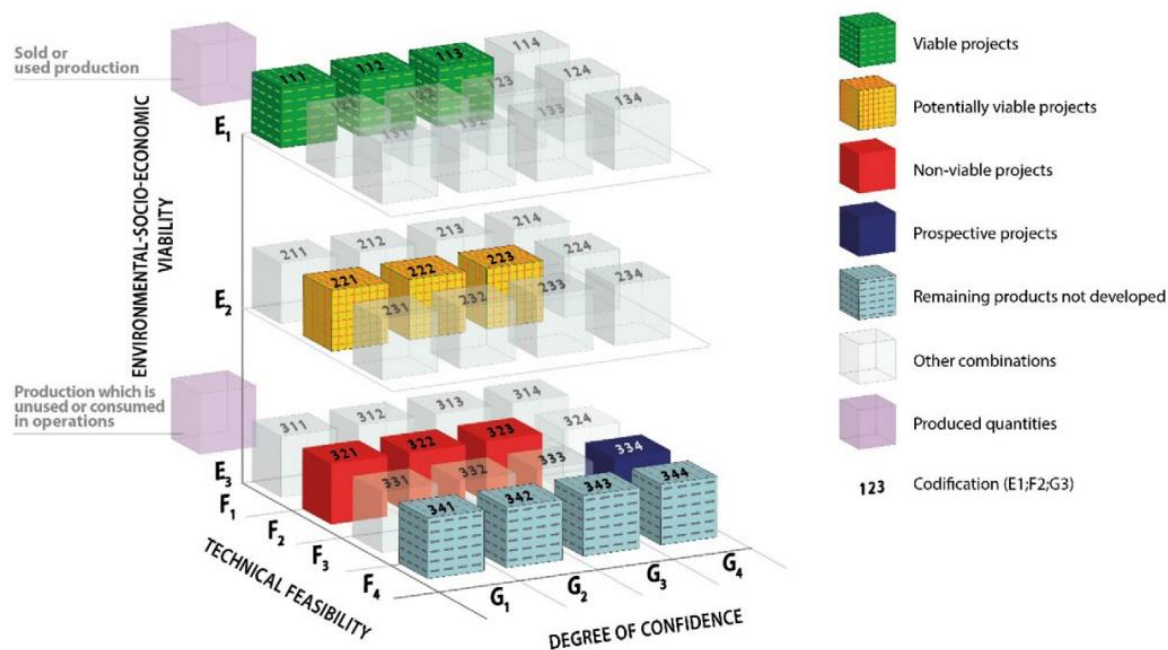


Figure 8-4: UNFC 2019 Project Maturity Classes, [282].

### 8.3 Implementation of societal embeddedness level for underground hydrogen storage

As presented in Section 8.2, the approaches proposed in [266, 267] provide a framework for assessing the readiness levels of a project as it matures through increasing levels of development, from both technological and social criteria. Many of the social criteria for UHS may be derived from other storage activities such as UGS and CO<sub>2</sub> storage. However, as hydrogen has different physiochemical characteristics with different associated impacts, and UHS will be deployed in a novel and emerging energy system context, there is also a need to (re)define these social aspects. Table 8-2 provides some examples. It is highly recommended to extend the identification of relevant aspects and elaborate the definition and specification for each SEL Dimension in the UHS context as required in Level 1 of the SEL framework (see Section 8.2.2).

Table 8-2: Preliminary list of social aspects that need identification and (re)definition in UHS context.

SEL Dimension	Examples of new social aspects to be considered, relative to current UGS
(1) Impacts on Environment	<ul style="list-style-type: none"> <li>Assessment of impacts over the entire UHS life cycle, including, e.g., impacts of hydrogen leakage and potential reaction by-products on the natural environment, atmospheric implications of hydrogen release (indirect greenhouse gas, [283]), carbon footprint of UHS activities, safety aspects related to potential induced seismicity events, facility hazards, explosions, etc.</li> <li>Strategies to deal with risks/negative impacts on the environment. What are acceptable norms?</li> <li>Competition for space between UHS and other subsurface and surface activities and functions.</li> <li>Cultural context and history, for example positive or negative experiences with similar storage technologies. This also interlinks with stakeholder involvement.</li> <li>Possible advantages and positive impacts (e.g., economic, infrastructure, etc.).</li> </ul>

(2) Stakeholder Involvement	<ul style="list-style-type: none"> <li>• Identification and evaluation of the relevant stakeholder environment, among others: UHS operators, UHS clients and end-users, hydrogen producers, importers, regulators, supervising authorities, local communities, water boards, NGOs, policy and decision makers, grid operators, research institutes.</li> <li>• What are the interests of these stakeholders? How can they have (positive or negative) influence on the project?</li> <li>• Trust in (local and national) governments as well as trust in operators.</li> <li>• What are the expectations of the stakeholders? Is it necessary to change these? Are they informed enough?</li> <li>• What is the knowledge level, what level of knowledge should they have, how does this influence the project?</li> <li>• Which level of knowledge suits which development phase and stakeholder type?</li> <li>• Means of communication and influence of (social) media, engagement and communication strategies for local communities.</li> </ul>
(3) Policy and Regulations	<ul style="list-style-type: none"> <li>• Policy ambitions, roadmaps and regional or national visions with regards to UHS deployment and upscaling</li> <li>• Permitting procedures, license framework, storage plans</li> <li>• Regulations for project oversight, monitoring and risk mitigation across entire UHS life cycle</li> <li>• Availability of storage, access rights to the energy infrastructure</li> <li>• Ownership, accountability of storage space, facilities, etc. (also after cessation of storage operations and decommissioning)</li> <li>• Interaction of policies, regulations and agreements on different levels (EU, national, regional)</li> <li>• Contacts/communications with and between different levels of governments/authorities: basis for policy development</li> <li>• Policy &amp; regulatory barriers &amp; stimuli, lock-ins*</li> <li>• (Industry) standards / certification</li> </ul>
(4) Market and Financial Resources	<ul style="list-style-type: none"> <li>• Societal costs and benefits including avoided energy system costs, energy security, employability, safety, avoided societal cost from avoided climate impacts, etc.</li> <li>• Financial risks &amp; benefits</li> <li>• Specific financial schemes to support UHS deployment and upscaling such as subsidies, tax incentives, etc.</li> <li>• Energy systems models: societal scenarios and UHS demand projections</li> <li>• Position of UHS in local market (which services, clients)</li> <li>• Business models and substitutes for UHS</li> <li>• Market maturity and Identification of market gaps</li> </ul>

\* In [284] the example is described of carbon lock-ins where the inertia of carbon emissions due to mutually reinforcing physical, economic, and social constraints, which are common to complex systems, constrain the rate and magnitude of carbon emission reduction

### 8.3.1 SEL Methodology

Based on their evaluations of CCUS at national levels, [266, 267] describe the following three steps for the application of SEL, i.e.:

- STEP 1:** Determine the starting point of SEL assessment,
- STEP 2:** Assess the SEL for each societal dimension,
- STEP 3:** Identify the overall SEL and societal challenges on each dimension.

The following sections evaluate each step in further detail.



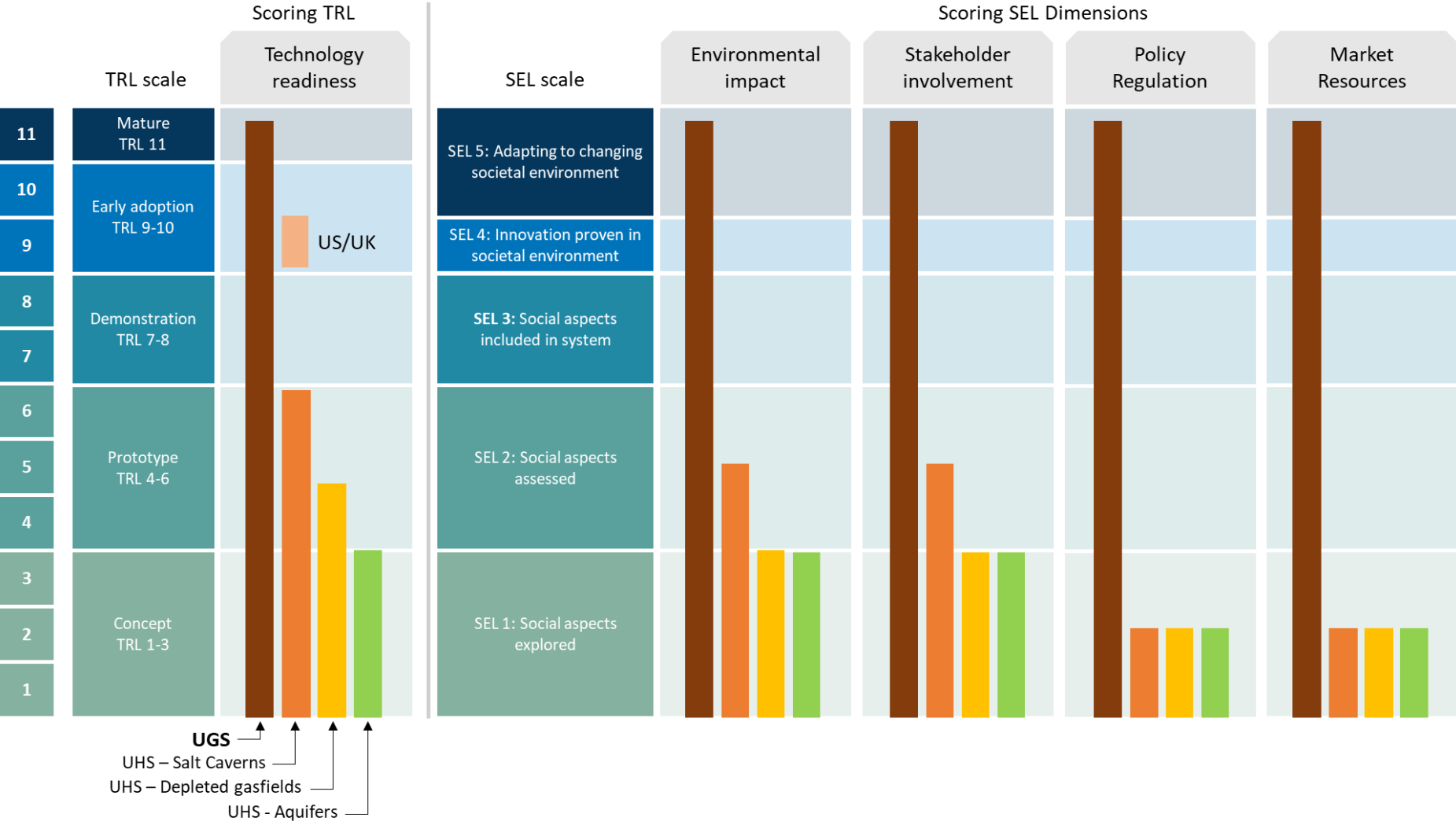


Figure 8-5: Example of a score card with conjectural estimation of technology readiness of various UHS options and the associated SEL estimates. The estimated technical and societal readiness of UHS is compared to UGS (dark maroon bars). The SEL estimates are still conceptual and were included only to illustrate the approach. Further definition and assessment are needed to confirm these estimates.

### **STEP 1: Starting point of SEL assessment**

This step provides insight in the level of societal embeddedness (SEL) that would be expected based on the current TRL of the UHS. Figure 8-5 uses a score-card approach [285] to display the TRL and SEL estimates for each geological option. These diagrams illustrate how the TRL – SEL approach may be presented during readiness assessments of a particular project. For example, pure hydrogen storage in porous reservoirs (depleted gas fields or aquifers) might have an estimated TRL of 3 – 5 which implies that SEL should be matured to level 1 – 2 (social aspects explored and assessment in progress). In many countries the TRL of UHS in salt caverns might be estimated at 5 – 6. In this case a SEL of 2 would be expected to be completed. The TRL of UGS is included in Figure 8-5 for comparison.

The estimation of TRL of the entire UHS system is given by the lowest level of any component in that UHS system. This means that the TRL of individual UHS components may be significantly higher, which may also be reflected in the assessment of SEL of that specific component. For example, the development of UHS in salt caverns depends on the construction and leaching of salt caverns. In countries where salt caverns are already being developed rock salt production or UGS this is considered as a technically and socially very mature component (e.g., good mining practices followed, environmental impacts understood, managed and mitigated, a level playing field with defined roles and responsibilities for all stakeholders involved, a mature regulatory framework, a well-functioning market). The injection and storage of hydrogen in these caverns, however, may still be at a pre-demonstration level while the identification of all social aspects is still incomplete. There is even thinkable that the social attitude towards salt solution mining alone will be impacted when the intention to use the resulting caverns for UHS would raise new societal concerns.

### **STEP 2: Assessment of the SEL for each societal dimension**

The SEL framework supports the assessment with milestones that need to be reached for each SEL dimension. If the level of the reference point (i.e., the expected SEL level for current TRL) is reached, then the next level can be assessed. If the level of the reference point is not reached, the previous level should be completed.

The outcome of the SEL assessment gives an overview of the actual SELs of the technology per societal dimension. Not every dimension has to be at the same level. Like TRL, the overall SEL of a technology is taken to be equal to the lowest reached SEL in any of the four dimensions. As is mentioned above, the actual SEL may for various reasons be lower than the level that would be expected on the basis of the TRL. In this case there would be a gap that needs to be bridged by raising the SEL to the expected level. Raising of the SEL comes with certain societal challenges for the different aspects involved, and these need to be taken into account for further development and deployment of the technology.

For example, suppose that a demonstration UHS project is planned in a given region or country in order to progress towards TRL 7 – 8, then the requirements for permitting such project should be known and local communities and stakeholders should be informed and included in the process (equivalent to reaching SEL 2). If the SEL is lower on these social aspects, then the development of the demonstration project may be delayed or have a higher chance of experiencing public resistance. In this case the challenge would thus be to first establish the social aspects (conditions and milestones) at such level that they can be tested for implementation in the system (SEL 3).

The SEL estimates for UHS in Figure 8-5 are compared conceptually to UGS. The further definition of the UHS SEL estimates may be improved on the basis of UGS experiences or examples for CCS projects. While UGS and UHS are based on similar principles, there are various caveats preventing a direct implementation of UGS SEL principles in UHS:

- The main difference between UGS and UHS is defined by the difference in chemical, thermal and physical properties of hydrogen vs. natural gas. Chapters 2 – 4 explain in detail how these differences impact the behaviour of hydrogen in an underground reservoir and the associated

surface facilities, the implementation of UHS, and the associated risks. In terms of SEL this has first of all consequences for Dimension 1 (e.g., how do hydrogen or its reaction products impact the environment when released, and how will the difference in operations influence the operational risks). Indirectly this will also impact Dimension 3 as regulations and policies must be adapted accordingly.

- A second difference is linked to the availability and cost of hydrogen vs natural gas. This includes the ways how hydrogen is being produced or supplied as well as the price of hydrogen. This has primarily consequences for Dimension 4 (Market and financial resources) and Dimension 2 (Stakeholder involvement).
- A third difference relates to the expected scale and speed of upscaling. This will impact regulations and policies addressed in Dimension 3, and which are needed to set targets and jurisdictions for spatial planning and licensing. It also impacts Dimension 2 (Stakeholder involvement) as it must be determined who is responsible for a timely and responsible upscaling, and who will implement such decisions.

With the preliminary estimates in Figure 8-5 it may be concluded that the overall SEL of UHS is still lower than what would be expected on the basis of UGS:

- Although most of the potentially expected environmental impacts are identified in Dimension 1, many of these are not yet evaluated (i.e., implications for development, strategies for monitoring and assessment, etc.).
- For Dimension 2, most stakeholders are identified, yet this may differ per country, depending on whether policy plans for a hydrogen value chain have been defined or not. In many cases there still is a debate concerning the role and responsibilities of stakeholders, and the public is still in need of information and education concerning storage of hydrogen.
- For Dimensions 3 (Policy and regulations) and 4 (Market and financial resources), the social aspects are still in need of further definition. The market has not been established yet and gaps must be identified and assessed. In many countries there is a need to establish policies for UHS deployment and upscaling and identification of gaps in the regulatory framework.

In the next steps of the SEL approach it is thus important to clearly specify which component of the UHS development is considered when assessing the societal aspects and identifying the associated challenges.

### ***STEP 3: Identify the overall SEL and societal challenges on each dimension***

This step evaluates the gap between the expected SEL (based on TRL) and the estimated SEL (based on local and national analysis). This gap evaluation results in an inventory and prioritization of actions that should lead to a maturation of SEL.

#### ***8.3.2 Generic workflow for combined TRL and SEL assessment***

The score-card approach (Figure 8-5) provides a synoptic report of readiness levels at a given point in the assessment process. However, progression through TRL may depend on SEL-related issues as well. For example, project elements such as site selection and screening, well design, and monitoring programs may be required to meet constraints from technological criteria as well as from applicable regulations for a particular jurisdiction. Therefore, progressing a potential UHS project from conception through to commercial operation may not depend on TRL alone. Accordingly, each stage in a project must assess both technical requirements (TRL) and societal requirements and expectations (SEL) to develop further (Figure 8-6).

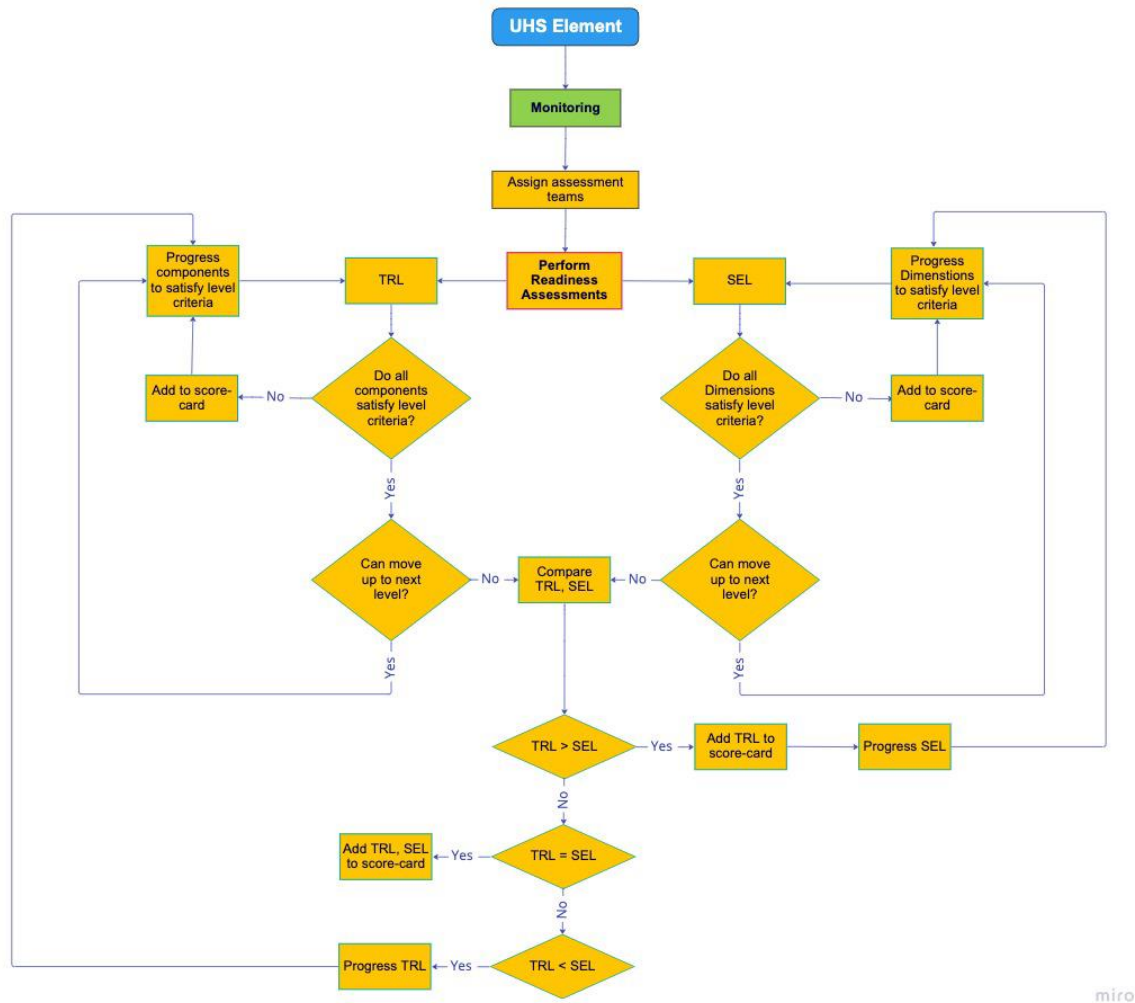


Figure 8-6: Incorporating dependencies between TRL and SEL at a particular stage of project development.

The score-card value for a particular stage of UHS development will highlight the particular areas in readiness (TRL, all four dimensions of SEL) that would require additional work before that element (e.g., monitoring) can progress to a higher level of readiness.

#### 8.4 Progressing maturity of underground hydrogen storage projects

The deployment of UHS hinges upon the existence of societal, political, economic, and regulatory frameworks that may differ widely in different regions. For example, [272] examined the regulatory and legal frameworks for underground gas storage in various countries around the world. They found that a set of technical standards, such as the well design for salt caverns, were implemented differently based on the local or regional framework. Their findings demonstrate how SEL could be applied to account for particular frameworks for a given technology.

The HyLAW project [286] evaluated the legal and administrative processes for several countries in Europe and Scandinavia that governed hydrogen and fuel cell technologies for grid-related applications. Its database provides access to applicable regulations while focusing attention on legal barriers to be removed. The project did not, however, consider UHS or its integration into pipeline or economic frameworks, nor did it include other global regions. A common element that underlies policies, practices, and regulations is a robust technical understanding of underground gas storage, regardless of the type of gas (natural gas, carbon dioxide, hydrogen). One recommendation of this

chapter therefore is for a project comparable to HyLAW to be performed to summarise the legal and administrative processes and barriers. This will enable to progress the technical and societal maturation (TRL and SEL) of UHS in various countries and geological settings around the world.

### 8.4.1 *Maturing social embeddedness of UHS projects*

To date only few examples for the implementation of SEL have been published. In [266] it is shown how the methodology can be applied to CO<sub>2</sub> sequestration. They evaluated SEL for CO<sub>2</sub> sequestration facilities by using national-level databases from the Netherlands, Norway, and Germany. This study further suggests a refinement of SEL by applying it at the local project scale. In [23] it also recommended applying TRL to individual projects after modifying it as needed for site-specific requirements. In contrast, the utility of SEL for individual UGS or UHS projects has not yet been evaluated.

The evaluation and demonstration of SEL at the project scale is considered of key importance to establish generic principles at the national scale. It is therefore recommended to select specific UHS pilot projects and facilities, which provide a platform to evaluate and test SEL principles. Further experiences on the applicability of SEL principles to UHS projects may be obtained by evaluating UGS projects that are technically and socially mature and have many similarities to UHS. It is suggested to establish a preliminary list of potential candidates across different parts of the world from different geological, cultural and societal settings. The exact approach and workflow for evaluating these projects should be determined in collaboration with the operators and the relevant stakeholders and authorities involved in the execution and permitting of these projects.

It is anticipated that managers and other key UHS facility personnel may consider SEL as a novel approach to societal engagement. Additionally, governments/regulators could be interested, especially in the case of projects being labelled as projects of national interest, and in which governments will be closely involved in the development. Typical questions and requirements that may be expected are summarized in Table 8-2.

The results of this evaluation of UHS facilities, at their level of potential application, will highlight areas for improvement and refinement of the SEL approach for UHS. The findings could help authorities, site owners and other stakeholders to start the development of risk governance strategies to address societal risks related to UHS deployment and upscaling.

## 8.5 Summary of findings and recommendations

The success and effectiveness of the implementation of a new technology greatly depends on the appropriate and timely societal embedding. Societal Embeddedness covers four main dimensions focusing on i) environmental impacts, ii) stakeholder involvement, iii) policy and regulations, and iv) market and financial resources. As the technology progresses from conceptualization towards implementation and full maturation, each of these dimensions needs to progress from exploring social aspects towards assessing and implementing social aspects in actual projects.

This chapter provides a first exploration of how the Societal Embeddedness framework and its dimensions can be defined and applied to UHS. The general conclusion is that the framework appears to provide a comprehensive and systematic coverage of the UHS scope with a differentiation between aspects that are defined as generic issues and aspects that are specifically defined for local and regional development.

All focus areas of societal engagement in this chapter are directly related to the SEL approach. The structured format of SEL provides guidance to operators, regulators, the public, and other stakeholders on how to organize and execute societal engagement to reach a satisfactory conclusion.

From a first explorative survey, the following key actions are identified for each dimension:

1. Environmental impacts
  - Assess all potential environmental impacts specific to UHS.
  - Establish risk governance strategies to minimize and mitigate impacts.
2. Stakeholder involvement
  - Extend identification and adaptation of stakeholder interests and involvement towards relevant parts of the hydrogen value chain.
  - Establish adequate knowledge base and communication strategies for all processes across the UHS life cycle.
3. Policy and Regulation
  - Adopt policy ambitions to support expected level of storage demand.
  - Develop and adopt regulations to support safe UHS deployment and prevent lock-ins.
4. Market and financial resources
  - Improve demand predictions.
  - Elaborate business models, assess financial risks and establish financial schemes to support the required level of deployment.

With the above comes the question as to where UHS developments stand with respect to individual social dimensions. This will require the collation of materials from the literature and other ongoing initiatives with respect to risks/environmental impacts, regulatory landscape, business models, etc. Such a compilation would be valuable from an operator perspective, as well as from a governmental and regulatory perspective. This leads to a need for defining actions and/or identifying best ways to progress projects to higher SEL in the individual dimensions. Besides identifying the current SEL for UHS, there is also the question of how to further mature the SEL in the best way.

In this respect, the following recommendations are made to mature the implementation of the Societal Embeddedness framework:

- Expand the assessment of the SEL for each social dimension, and if possible by distinguishing geographic differences.
- More detailed exploration of all relevant social aspects and associated challenges in each social dimension. This needs to be completed among others through stakeholder (expert and non-expert) interviews at local, national and international levels.
- Testing and assessing the various social aspects of existing and developing pilot and demonstration projects. Experiences may be incorporated from mature technologies such as UGS which have many characteristics in common.
- Working with interdisciplinary teams to develop and implement the SEL principles, to gain sufficient knowledge in all four social dimensions and to improve the representativeness and broader social support of results.
- Comparing SEL outcomes of different projects/countries/regions to 'learn' from each other and thus accelerate worldwide UHS development and deployment.

Because the utility of SEL for UGS or individual UHS projects has not yet been evaluated, it is recommended to select specific UHS pilot projects and facilities that provide a platform to evaluate and test SEL principles. The preliminary list of potential UHS projects across different parts of the world from different geological, cultural and societal settings, once evaluated, could then be compared to a reference case for SEL provided by the worldwide experience in UGS.



# CHAPTER 9

## Synthesis and Outlook



Experiences and challenges

Knowledge gaps and main recommendations

## 9 Synthesis and outlook

The application of hydrogen as a feedstock resource has been anchored within the petrochemical and fertilizer industry for many decades. The current hydrogen ecosystem as such is mainly established locally within these industrial clusters. While the share of renewable energy in the energy system continues to grow over the coming decades, there is also a need for low-carbon flexibility and balancing solutions in order to mitigate the increasing variability of energy production and demand and to secure energy supply at hourly to seasonal time scales. Next to the many small-scale, decentralised and surface-bound energy storage options, including batteries and heat storage, underground hydrogen storage (UHS) is considered to become a crucial technology to provide GWh – TWh scale storage capacities that are needed to support peak and seasonal energy demand at industrial and national grid scale, and thereby accommodate the steep growth of variable electricity generation from wind and solar.

This report presents an overview of the current state-of-art for underground storage of hydrogen and addresses existing knowledge gaps and potential barriers for development and future upscaling. Recommendations and guidelines are given to assess and demonstrate the geological, technical, commercial, environmental viability and to improve the societal embeddedness of this technology.

### 9.1 Experiences and challenges

Only four industrial sites (one in the United Kingdom and three in the United States) are connected to UHS facilities for pure hydrogen gas storage in salt caverns. These storage sites mainly serve as a strategic backbone for constant supply of hydrogen as a feedstock. Although these examples do not demonstrate the wider deployment of UHS in the energy system, they do prove that salt caverns can safely contain hydrogen.

Underground storage of natural gas in salt caverns, depleted hydrocarbon reservoirs, saline aquifers and lined rock caverns is very mature and commercially deployed to secure supply of natural gas. In Europe alone, there are over a hundred operating UGS sites, which are able to roughly supply a quarter of the total annual demand for natural gas (Chapter 1). Underground hydrogen storage targets the same reservoirs as UGS and considers similar functional and operational principles for the design and construction of facilities and wells. Despite the many technical similarities between UHS and UGS, there also exist some profound differences, mainly due to the higher reactivity and different chemical and physical properties of hydrogen compared to methane and natural gas. Laboratory-scale investigations indicate that injection, containment, and retrieval of pure hydrogen in porous rock formations may be successfully implemented, yet these investigations also show that the presence of hydrogen under certain geological conditions and certain types of reservoirs may trigger adverse effects that in turn may impact injection performance, containment, recovery and the quality of hydrogen. These impacts potentially result in safety issues around wells and (surface) facilities. The same would hold for salt caverns, which – apart from mechanical stability of the cavern heterogeneous structure – can also host bio-geochemical reactions and produce impurities in the stored hydrogen.

Besides UGS, there are a few sites across Europe where mixtures of hydrogen with various other gases (so-called town gas) have been successfully and commercially stored in porous rock reservoirs and salt caverns. Two locations have recently performed tests with the injection of hydrogen – natural gas mixtures in depleted gas fields. While limited in scale and not based on pure hydrogen, such experiences are of great importance to understand the behaviour of hydrogen in a real subsurface environment.

## 9.2 Knowledge gaps and main recommendations

Underground hydrogen storage is still an immature technology for which many barriers and uncertainties must be resolved to allow successful deployment and upscaling. The road towards a mature and commercial implementation of UHS is still long, yet the demand for storage capacities is starting to emerge and will likely grow fast after 2030. Synergy and collaboration between academic research and industrial innovation and development is key to overcome the still existing hurdles and to pave the way for demonstration and taking the learnings to enable implementation. Timely action is required from industry, governments and other stakeholders in order to close the knowledge gaps, reduce risks, build confidence and experience and thereby establish a full license to operate. Collaboration between these parties is essential to gain optimal experience from pilot and demonstration projects.

This report has presented these barriers and challenges for seven main thematic areas, i.e.:

- Geochemical and microbial processes and impacts,
- Storage integrity,
- Storage performance,
- Site screening, ranking and geological characterization,
- Facilities and wells,
- Economics,
- Societal embeddedness.

The following sections present the overarching recommendations that are considered key to enabling a viable demonstration and deployment of UHS. Further details on specific recommendations are provided in the respective chapters.

### 9.2.1 *Recommendation 1: Increase technological confidence in UHS based on lab, model and pilot tests, performed on multiple geological environments and with operational settings*

There is insufficient practical information and experience from real subsurface hydrogen injection and extraction activities in order to reliably predict and monitor the behaviour and impacts of hydrogen injection in porous reservoirs and salt caverns.

Key challenges and barriers:

- Critical processes and impacts (such as bio-geochemical reactions, hydrogen flow and migration, thermodynamic processes, and rock mechanical behavior) are mostly studied from isolated laboratory experiments and numerical models. There exist only a few hydrogen laboratories (mainly in Europe), which have published experimental data with hydrogen at subsurface-relevant pressures and temperatures. To facilitate more experiments with hydrogen across the world, establishment of publicly available laboratory protocols and benchmarking data platforms are crucial. There is also very little (public) information about hydrogen injection and extraction in real subsurface environments. The experiences from UGS can only be extrapolated to UHS to a limited extent, due to the very different physical and chemical characteristics of hydrogen vs. natural gas and methane. From geomechanical perspectives, however, UHS technology can benefit from the UGS experiences in both caverns and porous rock reservoirs.
- Porous reservoirs reveal a huge variation in their local geological characteristics (e.g., depth, shape, rock types, fluids, faults, mechanical behavior, overburden composition). Experiences often cannot simply be transferred from one location to another. Therefore, initial UHS projects will consequently have to deal with substantial uncertainties which propagate to many risk factors from operational to project-economic and safety.
- Monitoring of hydrogen behavior in the subsurface is still in an early stage of development. Some techniques are at low TRL levels and need to be tested in a real subsurface environment.

The lack of in-situ subsurface observations and measurements hampers the validation and matching of numerical models, which are also not yet fully developed. Consequently, the outcomes of such models may be highly uncertain, which leads to, e.g., higher operational, project-economic, and safety risks.

Call for action:

- Establish pilot and demonstration projects for UHS in porous rock formations and within different geological settings. Furthermore, establish more UHS pilots in salt caverns with open-access data. Ensure that these projects incorporate the extensive testing, sampling and monitoring programs, with publicly available data, integrated with other storage projects in order to establish a growing public knowledge base and trust, to reduce risks and increase public acceptability for future projects.
- As cavern storage has a higher technical readiness level than porous reservoir storage, the development of UHS may benefit from a stepped approach where initially caverns could provide initially required storage volumes in some markets, while simultaneously maturing the porous media storage opportunities.

### 9.2.2 Recommendation 2: Develop a market for UHS, identify and resolve market gaps

The market for UHS is still very immature. There is a lack of information on certain cost aspects, market regulations and revenues, and the long-term economic viability to justify the high investments associated with the development of UHS projects.

Key challenges and barriers:

- Future projections of hydrogen storage demand and the economic basis for UHS projects is often based on indicative and uncertain assumptions. This also concerns the concrete services and end-uses that are expected from UHS in the future energy system.
- Certain cost aspects of UHS development and operations are still uncertain while these may have a major impact on the project CAPEX and OPEX. Examples are costs of cushion gas, gas treatment and maintenance, plus workovers of facilities and wells.
- In the absence of practical experiences with UHS in a real subsurface environment, there may be significant uncertainties regarding the injection/extraction performance and the quality and recoverability of hydrogen, which translate to a high uncertainty of the project OPEX.
- Unclear future market regulations result in large uncertainty of revenues that can be generated from UHS operation, which can increase the investment risks for major industries.

Call for action:

- Investigate options to reduce and mitigate investment risks of early (pioneering) UHS projects to establish and improve the knowledge for reliable project economic assessments.
- Assess the criticality of UHS for security and balancing of energy supply/demand at national and international scales, including a comprehensive analysis of (societal) cost and benefits under different energy transition scenarios.
- Assess the need for national and international UHS market-regulation frameworks covering regulated and third-party access storage sites.
- Share operational experiences which can be gained and improved from scalable development of UHS in salt caverns and which may be extended to UHS development in porous rock reservoirs.

### 9.2.3 Recommendation 3: Improve and validate methods and strategies for risk assessment and uncertainty reduction

Existing information and models are still in need of improvements and further validation to support an integrated and reliable assessment and quantification of risks associated with the UHS technology.

This also concerns validated risk reduction measures, reliable hazard predictions, monitoring of risks, quantification of impacts, mitigation options, agreed standards and norms, etc.

Key challenges and barriers:

- Risks are often addressed on an individual and qualitative basis only (e.g., causes, processes). There is not (yet) a comprehensive and reliable, public domain information and knowledge base for a full and reliable quantification of risks.
- There are significant uncertainties in predicting many of the UHS related risks due to, among others, the lack of models that are validated with real-field monitoring data. Adequate governance of risks is hampered by the absence of clear standards, norms and possible lack experience with UHS at regulatory authorities.

Call for action:

- Establish an integrated risk management framework (e.g., bow-tie analysis) per UHS option, which identifies causes, prevention, mitigation and consequences around potential hazard events.
- Establish validated models and cause-to-consequence risk modelling toolboxes that can be applied to quantify specific risks for different operational scenarios and geological settings.
- Define common standards, norms and guidelines for assessing and managing UHS risks (part of regulatory framework and legislation).
- To increase the reliability of the predictions, real-field data needs to be obtained accurately based on field pilots and demonstrations, and also needs to be released public.

### 9.2.4 Recommendation 4: Establish a systematic approach towards societal embeddedness of UHS

The implementation and commercialization of UHS will only be possible with the acceptable level of societal embeddedness. The following actions are recommended to support governments, stakeholders and public in defining the framework and criteria for establishing a social license to operate.

Key challenges and barriers:

- The level of societal embeddedness of UHS may be too low for the upcoming phases of demonstration and implementation. This may lead to delays or even a halt of projects.
- Insufficient definition of social aspects may lead to uncertainties regarding the license to operate on the longer term. Investors may see this as a risk for their projects.

Call for action:

- At a national level, perform a comprehensive evaluation of each social dimension (i.e., environmental impacts, stakeholder involvement, policy & regulations, market & financial resources) and determine what is the ratio of the actual vs. the expected level of societal embeddedness according to the current technical readiness level.
- For each social dimension, formulate the required steps for reaching the societal embeddedness level that supports development and operation of demonstration projects
- Develop frameworks and strategies to engage the relevant public stakeholders from the beginning of the project, e.g., by the use of media, reports, press and open day events. Stimulate public participation with transparent information as a basis to objectively evaluate local benefits and impacts of UHS development.

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## Appendix A. Potential hazards and adverse effects

Table A-1: Overview of potential hazards and adverse effects resulting from hydrogen injection into and withdrawal from underground stores.

Cause/Process	Description of hazard or adverse effect	Impact	Relevancy
Microbial activity	<b>Gas mixture change/souring/toxicity:</b> Microbial activity can lead to a decrease of hydrogen, increase of H <sub>2</sub> S or methane, and increase/decrease of CO <sub>2</sub> . For H <sub>2</sub> S formation (a toxic and corrosive gas), sulphate needs to be present. Enhanced by the presence of hydrogen and easily degradable carbon sources	Performance, Well/Facility integrity, Operations, Safety, Economy	Predominantly porous rock and salt caverns
Microbial activity	<b>Steel corrosion:</b> Microbially influenced corrosion (MIC) can occur in environments with active microorganisms. Unknown whether hydrogen stimulates MIC (because of stimulation of microbial activity) or limits MIC (because of offering an alternative electron donor instead of Fe(0))	Performance, Well/Facility integrity, Operations, Safety, Economy	Predominantly porous rock and salt caverns
Microbial activity	<b>Microbial- induced plugging:</b> Microbial growth will lead to biofilm formation which can cause clogging. Also, mineral plugging can occur upon microbiologically mediated reactions. Lower permeability and performance	Performance, Operations, Economy	Predominantly porous rock and salt caverns
Geochemical activity	<b>Contamination with H<sub>2</sub>S and loss of hydrogen,</b> particularly in high temperature porous rock reservoirs	Wells, facilities, safety and economy	Predominantly porous rock, possibly salt caverns
Microbial and geochemical activity	<b>Dissolution of minerals and change in reservoir properties:</b> Microbial or chemical reactions can lead to the dissolution of reservoir minerals, e.g., carbonate and other easily dissolvable minerals.	Safety, Reservoir integrity	Predominantly porous rock
Hydrogen leakage, Microbial activity	<b>Groundwater pollution:</b> Hydrogen leakage from reservoirs into the groundwater will affect groundwater microbial communities and associated nutrient cycles.	Environment, Safety	Porous rock and salt caverns
Hydrogen migration, Geochemical activity	<b>Degrading sealing capacity of caprock:</b> Sub-grain scale/ intergranular processes, e.g., mineral dissolution/precipitation, crack growth, sorption	Caprock integrity, Environment, Safety	Porous rock
Hydrogen migration, Geochemical activity	<b>Diffusion and permeation through caprock:</b> Upward dispersion of hydrogen through the caprock, possibly amplified by H <sub>2</sub> -driven geochemical reactions and mineral dissolution/precipitation in caprock	Environment, Safety	Porous rock
Hydrogen migration, Geochemical activity	<b>Migration through fractures:</b> Sub-grain scale/ intergranular processes, e.g., mineral dissolution/precipitation, crack growth, hydrogen sorption impacting mechanical and transport properties of the seal.	Environment, Safety	Porous rock
Rock deformation, Cyclic loading	<b>Rock deformation and lower threshold for fault slip</b> due to fast-cyclic loading and high-pressure variation. Leading to possible fault slip and fracture development/propagation	Reservoir integrity, Safety, Operations	Porous rock

## Appendix A

Cause/Process	Description of hazard or adverse effect	Impact	Relevancy
Changing mechanical properties, Geochemical activity	<b>Subcritical crack growth due to weakening molecular bonds:</b> Mineral precipitation and dissolution in carbonate, sulphate, sulphide, and ferric-bearing reservoir rocks. Leading to possible fracture development/propagation	Reservoir integrity, Safety, Operations	Porous rock
Changing mechanical properties, Cyclic loading	<b>Progressive fatigue of reservoir rock</b> due to intergranular clay swelling/shrinkage cycles. Leading to possible fault slip and fracture development/propagation	Reservoir integrity, Safety, Operations	Porous rock
Hydrogen migration, Cyclic loading	<b>Damage zone permeation:</b> Cyclic changes in cavern pressure (frequency, magnitude) may lead to progressive hydrogen penetration into the surrounding damage zone. Damage zone increase due to overpressurisation caused by trapped hydrogen.	Caprock integrity, Safety, Operations	Salt caverns
Hydrogen/Brine migration/escape Fracturing	<b>Shear or hydraulic fracturing at cavern roof:</b> Overpressurisation in brine-filled caverns due to increasing temperature of brine (expansion) and simultaneous cavern convergence due to salt creep. Leading to leakage pathways for hydrogen, brine and additives. This is also a post-operation hazard.	Caprock integrity, Safety, Environment	Salt caverns
Salt creep	<b>Subsidence:</b> With increasing depth and temperature the visco-plastic behaviour of salt changes. Salt cavern walls will slowly move inwards if cavern pressure does not balance the lithostatic pressure. Small deviatoric stresses in the farther field, away from the cavern wall, may lead to increased creep and associated surface subsidence. This is also a post-operation hazard	Safety, Environment,	Salt caverns
Rock deformation Fault reactivation	<b>Induced seismicity:</b> Salt creep below brittle overburden rock could lead to movement along pre-existing faults.	Safety, Environment	Salt caverns
Salt creep	<b>Reduction of available storage volume:</b> Under certain conditions, salt creep can lead to cavern closure and loss of available storage volume	Performance, Operations, Economy	Salt caverns
Pressure limitations	<b>Lower working gas volumes:</b> The initial (original) high pressure of some depleted natural gas reservoirs may not be used as maximum working pressure for hydrogen storage due to technical and economic reasons	Performance, Operations, Economy	Porous rock
Invasion of water from aquifer	<b>Lower working gas volumes:</b> The working volume may decrease as water invades the reservoir from an adjacent (active) aquifer	Performance, Operations, Economy	Porous rock

## Appendix A

Cause/Process	Description of hazard or adverse effect	Impact	Relevancy
Reservoir fluids, Changing flow dynamics	<b>Reduced injection/withdrawal performance</b> presence of other gas/liquid phases., residual gases in the reservoir/cavern. Hydrogen loading with liquids (water, hydrocarbons) from the storage, changes in wettability	Performance, Operations, Economy	Porous rock
Hydrogen leakage	<b>Leakage via legacy wells:</b> decommissioned or unmapped boreholes and wells that have not been properly completed or abandoned	Safety, Environment, Economics	Porous rock
Hydrogen leakage, Salt Creep,	<b>Salt creep leading to well integrity problems:</b> Salt movement has been observed to squeeze or stretch wells, which could potentially result in leakage	Well integrity, Safety, Environment, Economics	Salt caverns
Air emissions	<b>CO<sub>2</sub>, NO<sub>x</sub>, H<sub>2</sub> thermal emissions</b> may be associated with parts of the hydrogen storage supply chain	Environment	Porous rock, Salt caverns
unforeseen technical or safety issues	<b>High costs for site abandonment</b> due to unforeseen technical or safety issues	Economy	Porous rock, Salt caverns
Hydrogeological processes	<b>Loss of cushion gas to formation:</b> Cushion gas may become partly irretrievable in formation and is a sunk cost	Economy	Porous rock
Availability of suitable reservoirs	<b>Cost of cushion gas may be needed:</b> Large volumes of cushion gas may be associated with available candidate reservoirs (especially porous formations) and present an unacceptably high capital cost	Economy, Performance	Porous rock
Hydrogen leakage, Improper well design/materials	<b>Unacceptable leak rates</b> through annular sealant (e.g., packer), micro-annulus.	Economy, Safety	Porous rock, Salt caverns
Hydrogen leakage, Post cementing operations, Geochemical activity	<b>Damage to annular cement</b> by post-cementing operations, causing leakage, and requiring remediation. Annular sealant chemical alteration by hydrogen exposure, change in properties, loss of sealing ability.	Economy, Safety	Porous rock, Salt caverns
Hydrogen leakage, Explosion and fire	<b>Fire or explosion resulting from hydrogen leaking</b> towards the surface, at the wellhead or in surface facilities. Risk of harming life (humans, animals), and causing environmental pollution, noise, intense light. Special attention must be paid to places at or near the well where hydrogen can accumulate and form an explosive cloud..	Safety, Environment, Operations, Economy	Porous rock, Salt caverns
Limited experience	<b>Unexpected “surprises” during development/operations and non-optimal solutions</b> due to limited practical experience, especially with hydrogen storage in reservoirs (no commercial sites yet and very few pilots). Potentially leading to higher costs and risks.	Economy, Performance, Operations, Safety	Porous rock, Salt caverns
Unexpected downtime	<b>High cost of repair and downtime:</b> Can be (very) significant, for example, excessive cost of suitable annular sealant, placement equipment and methods, and long waiting time for sealant to cure.	Economy, Operations	Porous rock, Salt caverns



## Appendix B. Overview of development and research projects

Table B-1: Overview of previous town gas projects. Source: [287].

Country	Project name	Type	Storage volume (million m <sup>3</sup> )	Operational years as town gas storage	Current status
Germany	Kiel	Salt cavern	78	Unknown	Repurposed as natural gas storage
	Bad Lauchstädt	Salt cavern and depleted gas field	670	Unknown	Repurposed as natural gas storage
	Kirchheiligen	Depleted gas field	240	Unknown	Repurposed as natural gas storage
	Hähnlein	Aquifer	160	Unknown	Repurposed as natural gas storage
	Eschenfelden	Aquifer	168	Unknown	Repurposed as natural gas storage
	Engelborstel	Aquifer	Unknown	1955 - 1998	Decommissioned
	Ketzin	Aquifer	130	1964 - 2000	Decommissioned
Czech Republic	Lobodice	Aquifer	100	1965 - 1995	Repurposed as natural gas storage
France	Beynes	Aquifer	330	1956 - 1972	Repurposed as natural gas storage

Table B-2: Overview of known projects or plans aiming for the development of sites where UHS will be tested, demonstrated or implemented.

Country	Project name	Type	Expected capacity	Development status	Expected year in use	Description
Argentina	<a href="#">Hychico</a>	Depleted gas field	Unknown, testing only	Testing		Investigating storage of blended hydrogen (10%) in depleted hydrocarbons reservoirs. Including geomethanation.
Austria	<a href="#">Sun Storage 2030</a>	Depleted gas field	Unknown	Construction		This facility aims to develop a safe, seasonal storage of hydrogen in depleted natural gas reservoirs.
	<a href="#">SunStorage</a>	Depleted gas field	Unknown, testing only	Testing completed	2016	Testing injection of 10% hydrogen in a gas field.
	<a href="#">SunConversion, FlexStore</a>	Depleted gas field	Unknown, testing only	Testing completed		Testing underground methanation with injection of hydrogen and carbon dioxide.
Belgium	<a href="#">Loenhout Hydrogen</a>	Aquifer	Unknown, testing only	Pre-feasibility		Tests with hydrogen-natural gas mixtures planned.
Denmark	<a href="#">Green Hydrogen Hub</a>	Salt cavern	200 GWh	Pre-feasibility	2025	Aims to be the first fully commercially viable, 100% green, large-scale hydrogen production, storage and CAES solution.
France	<a href="#">Hypster</a>	Salt cavern	3 Tonnes	Construction	2023	EU supported large-scale green underground hydrogen storage.
	<a href="#">Cerville</a>	Salt cavern	Unknown	Proposal		By creating a salt cavern at the storage site in Cerville (Meurthe-et-Moselle department), surplus hydrogen may be stored to ensure security of supply and the Emil'Hy flexibility requirements.
	<a href="#">HyGreen Provence</a>	Salt cavern	Unknown	Proposal	2028	By 2028, hydrogen gas will be stored in salt caverns on the Manosque storage site and distributed for a wide range of uses.
	<a href="#">HyGéo</a>	Salt cavern	1,5 GWh	Pre-feasibility	2024	Built on the site of a former salt cavern in the town of Carresse-Cassaber in the Nouvelle Aquitaine region, HyGéo will store approximately 1.5 GWh of energy.

Country	Project name	Type	Expected capacity	Development status	Expected year in use	Description
Germany	<a href="#">H2Cast</a>	Salt cavern	Unknown, scalable	Testing	2024	Demonstrate the feasibility of large-volume underground storage of hydrogen and to prove the suitability of the salt caverns in Etzel for hydrogen storage.
	<a href="#">Jemgum storage</a>	Salt cavern	48 million m <sup>3</sup>	Pre-feasibility, FEED	2030	As part of a feasibility study, the suitability of an existing cavern of the Jemgum natural gas storage facility for storing hydrogen is analysed.
	<a href="#">Krummhörn</a>	Salt cavern	0,25 million m <sup>3</sup>	Pre-feasibility	2024	Project to store 100% hydrogen in the former Krummhörn natural gas storage facility. Commissioning of the demonstration plant with a storage volume of up to 0,25 million m <sup>3</sup> of hydrogen planned by 2024.
	<a href="#">Westküste 100</a>	Salt cavern	Unknown	Pre-feasibility		It is planned that a cavern storage system for hydrogen storage will convert the available wind energy into a continuous stream of hydrogen for industrial use.
	<a href="#">Bad Lauchstädt</a>	Salt cavern	150 GWh	Pre-feasibility		Green hydrogen will be converted from a nearby wind farm, stored temporarily in a salt cavern specially equipped for this purpose. Fed into the hydrogen network of the chemical industry based in central Germany and used in the future for urban mobility solutions.
	<a href="#">GET H2 Gronau-Epe</a>	Salt cavern	28 million m <sup>3</sup>	Planning, permitting	2027	One is planning to expand the existing above-ground facilities to include facilities for injection and withdrawing hydrogen and store it in caverns. The first stage of construction, the plant will be constructed in such a way that approximately 6 million m <sup>3</sup> of hydrogen may be in stock and thereof a volume of 28 million m <sup>3</sup> will be available for customers to store hydrogen.
	<a href="#">HyCAVMobil Rüdersdorf</a>	Salt cavern	6 Tonnes	Construction	2022	Construction of the test cavern commenced in February 2021. The cavern will be filled with hydrogen for the first time in spring 2022. The findings produced by the small research cavern should be easily transferable to caverns with a volume a thousand times larger. The aim is to use caverns with a capacity of 0,5 million m <sup>3</sup> for large-scale hydrogen storage in the future.

Country	Project name	Type	Expected capacity	Development status	Expected year in use	Description
Hungary	<a href="#">Aquamarine</a>	Depleted gas field	Unknown	Proposed		As part of the Aquamarine project one is intending to implement an electrolysis system with approximately 2,5 MW total performance and the corresponding hydrogen gas preparatory technology at the Kardoskut Underground Gas Storage site. The hydrogen produced in this way mixed with natural gas will be utilized within the Gas Storage Ltd.'s own gas-operated equipment.
Ireland	<a href="#">Green hydrogen @Kinsale</a>	Depleted gas field	3 TWh	Pre-feasibility		This project – pending licence and planning approvals – could have the potential to store up to 3 TWh of green hydrogen and hydrogen carriers. a comprehensive work programme has begun, comprising of subsurface analysis, mineralogy, capacity modelling, injection and withdrawal rates, compression, drilling evaluation, well design, retention assurance, monitoring, electrolysis and infrastructure tie-in.
Italy	<a href="#">North Adriatic Hydrogen Valley</a>	Depleted gas field	Unknown			An evaluation of potential gas fields and aquifers can be found <a href="#">here</a> .
Netherlands	<a href="#">HyStock</a>	Salt cavern	6 kTonnes	FEED and permitting	2027	First borehole tests and demonstration successfully finished in 2022. One cavern in 2027. The plan is to upscale the capacity to 4 caverns by 2030.
Poland	<a href="#">Damaśławek</a>	Salt cavern	Unknown		2030	The project calls for the first hydrogen cavern to be operational around 2030. The location and geological conditions allow for the creation of a storage facility of key importance to the energy security of Poland and the construction of the entire hydrogen economy. The storage facility can ideally fit into hydrogen clusters that will be created around industrial centres as well as offshore and renewable energy storage facilities.

Country	Project name	Type	Expected capacity)	Development status	Expected year in use	Description
Portugal	<a href="#">Sines H2 Hub, Carrico</a>	Salt cavern		Pre-feasibility		Large-scale industrial project for the production of green hydrogen in Sines with the capacity to integrate, simultaneously, the dimensions of production, processing, storage, transportation (internal and export) and consumption. Assessment of UHS at Carrico site can be found <a href="#">here</a> .
Slovakia	<a href="#">H2I</a>	Depleted gas field		Prefeasibility		The first phase of H2I S&D has experts seeking an appropriate location for storing hydrogen mixed with natural gas. Once an appropriate underground geological structure has been identified, laboratory research will then be carried out.
Spain	<a href="#">Undergy</a>	Depleted gas field		Pre-feasibility		Technologies for the development of seasonal renewable energy storage using green hydrogen as part of a smart grid.
Sweden	<a href="#">HyBRIT</a>	Lined rock cavern		Testing	2024	The pilot plant has a size of 100 m <sup>3</sup> . At a later stage, a full-scale hydrogen gas storage facility measuring 0,1 to 0,12 million m <sup>3</sup> may be required.
UK	<a href="#">Teeside</a>	Salt cavern	27 GWh	Operational	1972	Pure hydrogen storage for industry feedstock supply.
	<a href="#">ANGUS</a>	Depleted gas field		Pre-feasibility		Project to connect Saltfleetby facility to the UK National Grid and investigate possibility for storage and methanation.
	<a href="#">HySecure</a>	Salt cavern	40 GWh	Pre-feasibility		Demonstration project to build a salt cavern for hydrogen storage at Stublach (UK), the UK's largest natural gas storage facility.

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Country	Project name	Type	Expected capacity	Development status	Expected year in use	Description
US	<a href="#">Clemens Dome</a>	Salt cavern	82 GWh	Operational	1983	Pure hydrogen storage for industry feedstock supply.
	<a href="#">Moss Bluff</a>	Salt cavern	125 GWh	Operational	2007	Pure hydrogen storage for industry feedstock supply.
	<a href="#">Spindle Top</a>	Salt cavern	278 GWh	Operational	2016	Pure hydrogen storage for industry feedstock supply.
	<a href="#">Advanced clean energy storage</a>	Salt cavern	300 GWh	FEED	2025	Will consist of two caverns with capacities of 150 GWh, to store hydrogen generated by an adjacent 840 MW hydrogen-capable gas turbine combined cycle power plant.



Table B-3: Overview of UHS research facilities and projects that are relevant or mentioned in this report.

Country	Project name	Description
Austria	<a href="#">BIOPore</a>	Investigate the microbial growth and the resulting consequences on the pore scale to the medium scale.
Europe	<a href="#">HyStories</a>	Investigating hydrogen technologies for storage of pure hydrogen in depleted fields or aquifers.
	<a href="#">HyUSPRe</a>	Investigating the feasibility and potential of implementing large-scale storage of renewable hydrogen in porous reservoirs in Europe.
	<a href="#">HyUnder</a>	Assessing the potential actors and business models for large-scale underground hydrogen storage in Europe (2012-2014).
France	<a href="#">Abiotic Reactivity of minerals at elevated H<sub>2</sub> concentrations</a>	Exploring fluid-rock alteration processes at play within deep aquifers pressurized with hydrogen.
Germany	<a href="#">HyInteger</a>	Investigating the influence of microbial metabolism on the material integrity in wells.
	<a href="#">H<sub>2</sub> React/H<sub>2</sub> React Phase2</a>	Research on fundamental aspects of underground hydrogen storage. The project aims to derive experimental data on the kinetics of chemical reactions and microbial processes as well as on transport mechanisms of molecular hydrogen in deep geological systems under in-situ conditions.
	<a href="#">UMAS</a>	Project investigates the technical, economic and socio-economic feasibility as well as the ecological potential of underground methanation in aquifer storage.
	<a href="#">HyPos - H<sub>2</sub>UGS</a>	Development of a standardized and transferrable methodology for the future construction and conversion of salt caverns for hydrogen storage.
	<a href="#">TestUM-II Aquifer</a>	Geophysical and hydrogeological test field for the investigation and monitoring of reactive multi-phase transport processes in shallow aquifers induced by the use of the subsurface. follow-up project to TestUM Aquifer.
	<a href="#">Bio-UGS</a>	Investigates the targeted conversion of carbon dioxide and green hydrogen to methane in underground gas storage facilities by using natural existing microorganisms.
	<a href="#">CliMb</a>	Investigate the feasibility of both transformation processes by coupling experimental studies with numerical modelling and simulations in a multi-scale approach reaching from micro to macro-scale.

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Country	Project name	Description
Netherlands	<a href="#">ADMIRE</a>	Multi-scale numerical-experimental analyses of hydro-thermo-mechanics of UHS for site selection and operation, based on high-PT hydrogen lab.
	<a href="#">Caves&amp;Waves</a>	Induced seismicity risks of underground hydrogen storage.
	<a href="#">SafeInCave</a>	Mechanics of cavern storage, reservoir scale simulator for analyses of the time-dependent salt cavern state-of-the-stress, under cyclic loading for storage of hydrogen.
	<a href="#">HyStoreReact</a>	Advance fundamental understanding of the technical feasibility of UHS in salt caverns and porous reservoirs, by investigating the effects of geo- and biochemical reactions of hydrogen with rocks, fluids and microorganisms in the subsurface.
New Zealand	<a href="#">Pūhiko Nukutū</a>	Assessment of the technical viability, cost-effectiveness, and social-environmental impacts of storing large volumes (>50 million m <sup>3</sup> ) of hydrogen in sedimentary rock formations of the Taranaki Basin, New Zealand
Norway	<a href="#">Hydrogeni</a>	Centre to support a sustainable hydrogen economy in Norway and Europe.
	<a href="#">HyPE</a>	Laboratory studies of the physical and microbial processes that determine subsurface working gas capacity, deliverability, and injection rates for hydrogen in porous media. In addition, there will be developed a fully coupled numerical simulator based on new laboratory data from hydrogen storage related experiments.
	<a href="#">HyValue</a>	Develop knowledge, methodology and innovative solutions for hydrogen energy carriers to build and support a competitive hydrogen energy sector.
	<a href="#">CSSR</a>	Provide needed research to meet the challenges and explore promising opportunities of reservoir operations in a zero-emissions future.
	<a href="#">Biorisks in salt caverns</a>	Gain important knowledge on the types of halophilic microbes present in salt caverns, and whether they are affected by- or will affect hydrogen storage.
UK	<a href="#">GeoEnergy Observatory, Cheshire</a>	Borehole array suitable for understanding flow through porous rocks at site scale.
	<a href="#">HyStorPor</a>	Investigating the potential for hydrogen storage in porous reservoir rocks in the UK.
	<a href="#">IDRIC</a>	Addresses key multi-disciplinary and cross-cutting challenges of industrial decarbonization, including development of UHS.
US	<a href="#">SHASTA</a>	Determine the viability, safety, and reliability of storing pure hydrogen or hydrogen-natural gas blends in subsurface environments.

