HyUSPRe

Hydrogen **U**nderground **S**torage in **P**orous **Re**servoirs

Guidelines for reservoir and site suitability assessment for underground hydrogen storage in porous formations

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Please cite this report as: Farajimoghadam, F., Heinemann, N., Edlmann, K., Sousa, D., Ahn, A.-C., Hagemann, B., Hogeweg, S., ter Heege, J., Groenenberg, R., 2024: Guidelines for reservoir and site suitability assessment for underground hydrogen storage in porous formations, H2020 HyUSPRe project report. 28 pp

This report represents HyUSPRe project deliverable number D6.4

The HyUSPRe consortium

Funded by

Clean Hydrogen Partnership

Co-funded by the European Union

Acknowledgement

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under grant agreement No 101006632. This Joint Undertaking receives support from the European Union’s Horizon 2020 research and innovation programme, Hydrogen Europe and Hydrogen Europe Research.

Disclaimer

Executive summary

The HyUSPRe project focuses on evaluating the feasibility and potential of implementing underground hydrogen storage (UHS) in porous reservoirs in Europe. This initiative aligns with the broader European goal of transitioning to a net-zero emissions energy system by 2050, whereby an important role is foreseen for hydrogen as a versatile clean energy carrier and fuel. The project's primary objectives include assessing the technical feasibility and risks of UHS and developing a roadmap for its deployment. A combination of laboratory-scale experiments and integrated modeling efforts were employed to understand the geochemical, microbiological, flow and transport processes within porous reservoirs.

The guidelines for reservoir and site suitability assessment presented here offer a structured approach to site selection, detailing the stages from initial screening to deployment of hydrogen storage systems. These stages include pre-feasibility assessment, feasibility assessment, and post-feasibility assessment, ensuring a thorough evaluation of potential sites to minimize risks and optimize resources. This structured approach ensures that all relevant factors are considered, providing a clear framework for decision-making and implementation.

Key findings from the project highlight several critical aspects: UHS in porous reservoirs may induce geochemical reactions that can alter the reservoir's physical and chemical properties. These reactions are significantly influenced by environmental conditions in the reservoir (temperature, pressure), composition and pH of formation water, mineral composition, and the presence of gases like methane and carbon dioxide (CO2). Experimental results indicate that hydrogen can drive the reduction of minerals, such as pyrite, generating hydrogen sulfide (H_2S), and that reactions can affect the reservoir's porosity and permeability, potentially impacting performance. Thorough site-specific geochemical assessments are needed to ensure the feasibility and safety of UHS projects.

The project identified that microbial activities, including sulfate reduction, methanogenesis, and acetogenesis, play a key role in hydrogen storage. These processes can consume stored hydrogen and produce byproducts like H_2S, which may compromise well integrity, requiring gas treatment post-withdrawal. Proper collection and handling of samples taken from reservoirs, and incubation in laboratories under conditions representative of those in storage reservoirs are important for accurately assessing microbial risks. Continuous monitoring and advanced analytical techniques are useful for understanding microbial growth dynamics and their effects on hydrogen storage.

The flow behavior of hydrogen in porous reservoirs differs significantly from that of natural gas due to hydrogen's unique properties, such as lower density and higher diffusivity. The flow behavior of hydrogen in porous reservoirs differs significantly from that of natural gas due to hydrogen's unique properties. General parameters such as density, compressibility, and viscosity can be calculated for a reservoir based on pressure and temperature conditions. However, site-specific parameters such as diffusive/dispersive forces and wettability are strongly influenced by the rocks and fluids in the reservoir. Consequently, site-specific investigations are necessary to accurately determine hydrogen's compressibility, density, viscosity, and interactions with reservoir fluids and rock matrices. Relative permeability and capillary pressure measurements, along with solubility and diffusivity studies, are critical for understanding hydrogen transport and distribution within the reservoir. Field-scale simulations highlighted the importance of gas-gas mixing and gravity segregation effects.

Cyclic hydrogen injection and withdrawal can pose challenges to the reservoir near-well areas, potentially affecting well systems. Experimental studies on well cement and rock samples showed minor to no effects of hydrogen exposure under cyclic loading. However, it remains

helpful to conduct thorough durability assessments to ensure long-term stability and integrity of storage systems.

Numerical models are important for translating laboratory and pilot findings to field-scale applications, predicting gas behavior, optimizing storage operations, and assessing risks. The HyUSPRe project demonstrated that open-source simulators like DuMu^x and proprietary software like CMG's GEM are effective for modeling complex transport processes and bio-reactive interactions. Compositional models are particularly necessary for accurately predicting gas mixing and hydrogen concentrations in the withdrawal stream.

Overall, the HyUSPRe project provides a comprehensive understanding of the various factors influencing the feasibility and safety of UHS projects. The project's experimental results were largely positive, demonstrating that, with proper management and thorough assessments, porous reservoirs are suitable for hydrogen storage. These findings pave the way for more informed decision-making and effective implementation strategies.The guidelines presented in this document aim to facilitate a systematic and thorough approach to developing hydrogen storage technologies. By adhering to these guidelines, stakeholders can ensure a more efficient and safer deployment of hydrogen storage systems, aligning with the goals of sustainable energy transition.

About HyUSPRe

Hydrogen **U**nderground **S**torage in **P**orous **Re**servoirs

The HyUSPRe project researches the feasibility and potential of implementing large-scale underground geological storage of renewable hydrogen in Europe. This includes the identification of suitable porous reservoirs for hydrogen storage, and technical and economic assessments of the feasibility of implementing large-scale storage in these reservoirs to support the European energy transition to net zero emissions by 2050. The project will address specific technical issues and risks regarding storage in porous reservoirs and conduct an economic analysis to facilitate the decision-making process regarding the development of a portfolio of potential field pilots. A techno-economic assessment, accompanied by environmental, social and regulatory perspectives on implementation will allow for the development of a roadmap for widespread hydrogen storage by 2050; indicating the role of large-scale hydrogen storage in achieving a zero-emissions energy system in the EU by 2050.

This project has two specific objectives. Objective 1 concerns the assessment of the technical feasibility, associated risks, and the potential of large-scale underground hydrogen storage in porous reservoirs for Europe. HyUSPRe will establish the important geochemical, microbiological, flow and transport processes in porous reservoirs in the presence of hydrogen via a combination of laboratory-scale experiments and integrated modelling and establish more accurate cost estimates to identify the potential business case for hydrogen storage in porous reservoirs. Suitable storage sites will be identified, and their hydrogen storage potential will be assessed. Objective 2 concerns the development of a roadmap for the deployment of geological hydrogen storage up to 2050. The proximity of stores sites to large renewable energy infrastructure and the amount of renewable energy that can be buffered versus time varying demands will be evaluated. This will form a basis for developing future scenario roadmaps and preparing for demonstrations.

Document information, revision history, approval status

Document information

Title:	Guidelines for reservoir and site suitability assessment for underground hydrogen storage in porous formations
Lead beneficiary:	FBK
Contributing beneficiaries:	UEDIN, WUR, TUC, TNO
Due date:	M31 (April 2024)
Dissemination level:	Public
Published where:	HyUSPRe website
Recommended citation:	Farajimoghadam, F., Heinemann, N., Edlmann, K., Sousa, D., Ahn, A.-C., Hagemann, B., Hogeweg, S., ter Heege, J., Groenenberg, R., 2024: Guidelines for reservoir and site suitability assessment for underground hydrogen storage in porous formations, H2020 HyUSPRe project report. 28 pp

Revision history

Version	Name	Delivery date	Summary of changes
V01	F. Farajimoghadam	05.03.2024	Proposal for outline
V02	F. Farajimoghadam	17.06.2024	Final draft delivered
V03	H. Cremer	17.06.2024	Final formatted version

Approval status

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List of abbreviations

Abbreviation	Meaning
UHS	Underground Hydrogen Storage
TRL	Technology Readiness Level
EU	European Union
ACS	Advanced Control System
DUNE	Distributed and Unified Numerics Environment
EAGE	European Association of Geoscientists and Engineers
EIA	Environmental Impact Assessment
GIS	Geospatial Information Systems
XRD	X-ray diffraction spectroscopy
SEM	Scanning Electron Microscopy
EDX	Energy Dispersive Spectroscopy
HPLC	High-Performance Liquid Chromatography
PVT	Pressure Volume Temperature

1 Introduction

This document outlines guidelines for the decision-making process at Technology Readiness Level (TRL) 4, focusing on reservoir and site suitability assessments for hydrogen storage in porous formations. These guidelines can help to advance UHS towards pilot-scale demonstration (TRL 5-6), representing a critical step towards full-scale deployment of UHS. The primary aim of this document is to provide a framework for site selection, detailing the stages from initial screening to final implementation of hydrogen storage systems. The framework is designed to guide project managers, engineers, decision-makers, and other stakeholders that have an interest in the development and deployment of UHS. It outlines a structured approach that we anticipate will be valuable for site selection and implementation processes.

The guidelines presented here are part of a broader process that includes pre-feasibility assessment, feasibility assessment, and post-feasibility assessment stages. This structured approach ensures a thorough evaluation of potential sites, minimizing risks and optimizing resources for UHS implementation.

The pre-feasibility assessment involves several key actions critical for laying the groundwork before conducting detailed site-specific assessments. This stage begins with an initial screening, which is a preliminary evaluation of a wide range of potential sites based on general criteria such as geological characteristics, proximity to infrastructure, and regulatory considerations. This stage acts as a kill criteria phase, where unsuitable sites are eliminated, resulting in a shortlist of potential candidates. Following the initial screening, a more detailed evaluation is conducted on the shortlisted sites. This involves gathering specific information about each site, including geological surveys, land ownership details, and environmental impact assessments. Feasibility studies are then conducted to assess the technical, economic, and environmental viability of each shortlisted site. These studies may involve laboratory tests, simulations, and cost-benefit analyses, leading to the selection of one or more candidate sites for further detailed assessment.

The feasibility assessment, which lies between the pre-feasibility and post-feasibility assessments, involves a thorough examination of the selected candidate sites to validate their suitability for hydrogen storage. This includes detailed geological modeling, reservoir performance simulations, and comprehensive risk assessments. Once this detailed examination is complete, the candidate sites are ranked based on performance metrics and other relevant criteria. This ranking stage provides a prioritized list of sites, facilitating informed decision-making.

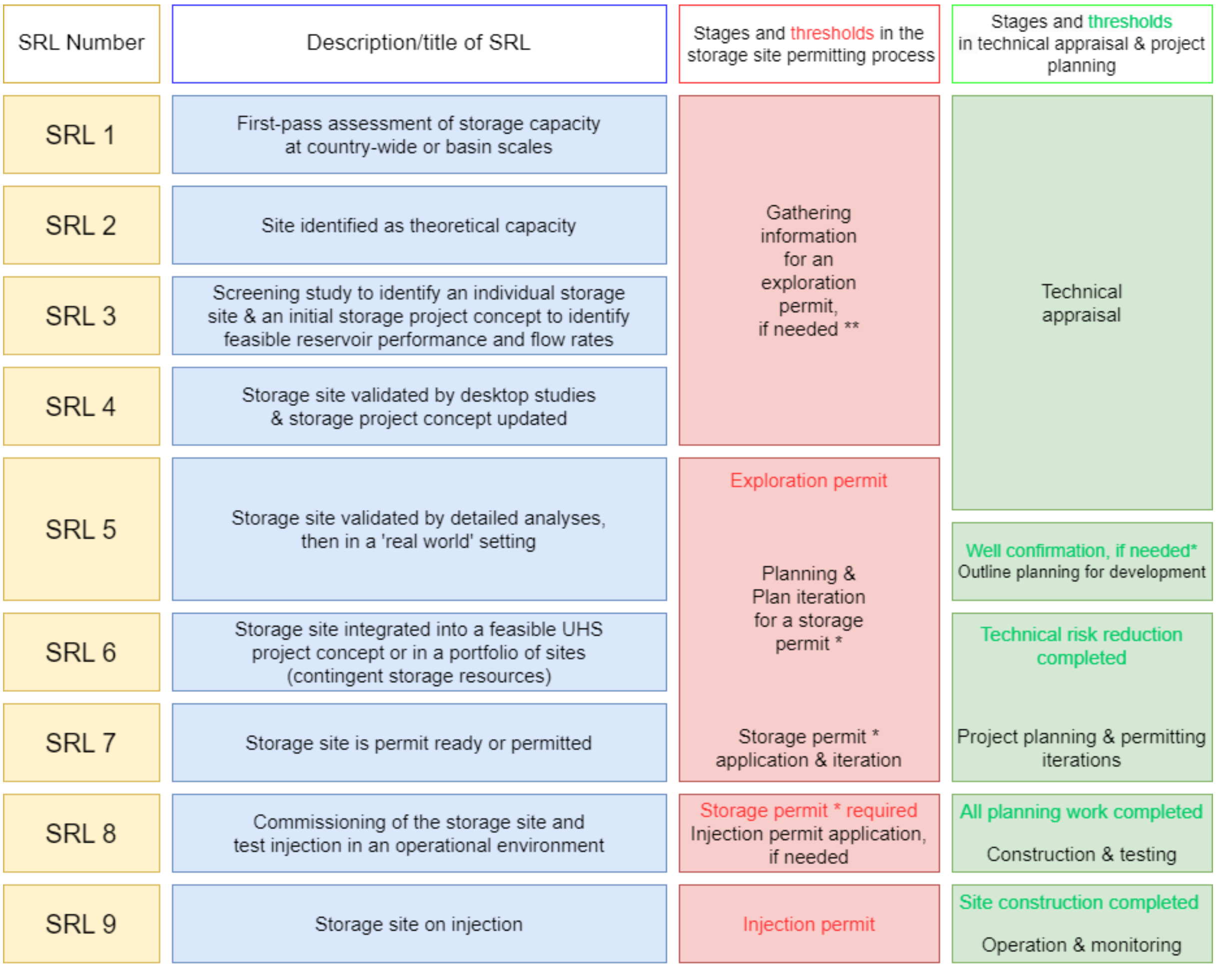
Following the feasibility assessment, the post-feasibility assessment includes several critical stages. First, the decision-making process involves reviewing the assessment results to determine if the sites meet the necessary technical, economic, and environmental criteria. Due diligence assessments are conducted at this stage to further evaluate the shortlisted sites, ensuring all aspects have been thoroughly considered. If a site is deemed suitable, the next step is the design of the hydrogen storage system. This involves determining the size, configuration, and infrastructure requirements of the storage facilities. Once the storage system design is finalized, regulatory approval must be obtained. This involves securing the necessary permits and meeting all regulatory requirements for safety, environmental protection, and land use.

Finally, after obtaining regulatory approval, the implementation of the storage system begins. This stage includes the construction and setup of the hydrogen storage facilities. It is advantageous to continuously monitor the operation of the storage system to ensure safety and efficiency, making adjustments as necessary to maintain optimal performance.

This document provides the necessary context and detailed guidelines to help readers understand the overall process of site selection for hydrogen storage. By outlining the stages from initial screening to final implementation, the guidelines aim to facilitate a systematic and thorough approach to developing hydrogen storage technologies.

2 Strategic evaluation process for hydrogen storage sites

The decision-making process for assessing reservoir and site suitability for hydrogen storage in porous formations within the HyUSPRe project involves several structured stages: Pre-Feasibility Assessment, Feasibility Assessment, and Post-Feasibility Assessment. Each stage is important for ensuring the thorough evaluation of potential sites, minimizing risks, and optimizing resources for hydrogen storage implementation. Figure 1 depicts the Storage Readiness Levels (SRLs) framework developed for UHS storage. It provides a systematic approach to storage site permitting and project planning. The principles and stages outlined in the SRLs framework offer valuable insights and can be effectively applied to UHS projects, ensuring a comprehensive evaluation process. Figure 1 illustrates the SRLs framework, highlighting the stages and thresholds in the storage site permitting process and technical appraisal. This figure is useful for understanding how each phase in the decision-making process corresponds to specific SRLs, ensuring a structured and methodical approach to hydrogen storage site selection and evaluation.



SRL Number	Description/title of SRL	Stages and thresholds in the storage site permitting process	Stages and thresholds in technical appraisal & project planning
SRL 1	First-pass assessment of storage capacity at country-wide or basin scales	Gathering information for an exploration permit, if needed **	Technical appraisal
SRL 2	Site identified as theoretical capacity		
SRL 3	Screening study to identify an individual storage site & an initial storage project concept to identify feasible reservoir performance and flow rates		
SRL 4	Storage site validated by desktop studies & storage project concept updated		
SRL 5	Storage site validated by detailed analyses, then in a 'real world' setting	Exploration permit Planning & Plan iteration for a storage permit * Storage permit * application & iteration	Well confirmation, if needed* Outline planning for development
SRL 6	Storage site integrated into a feasible UHS project concept or in a portfolio of sites (contingent storage resources)		Technical risk reduction completed Project planning & permitting iterations
SRL 7	Storage site is permit ready or permitted		
SRL 8	Commissioning of the storage site and test injection in an operational environment	Storage permit * required Injection permit application, if needed	All planning work completed Construction & testing
SRL 9	Storage site on injection	Injection permit	Site construction completed Operation & monitoring

* Equivalent of storage permit relevant to national jurisdiction

***Figure 1. SRLs framework, stages and thresholds in the storage site permitting process and storage project technical appraisal and planning (green). The thresholds for permitting are illustrated and labelled in red. The technical appraisal and planning thresholds are illustrated and labelled in green. **An exploration permit or well confirmation may not be needed for re-use of a hydrocarbon field for UHS storage. Figure modified from Akhurst et al., 2021*[1].**

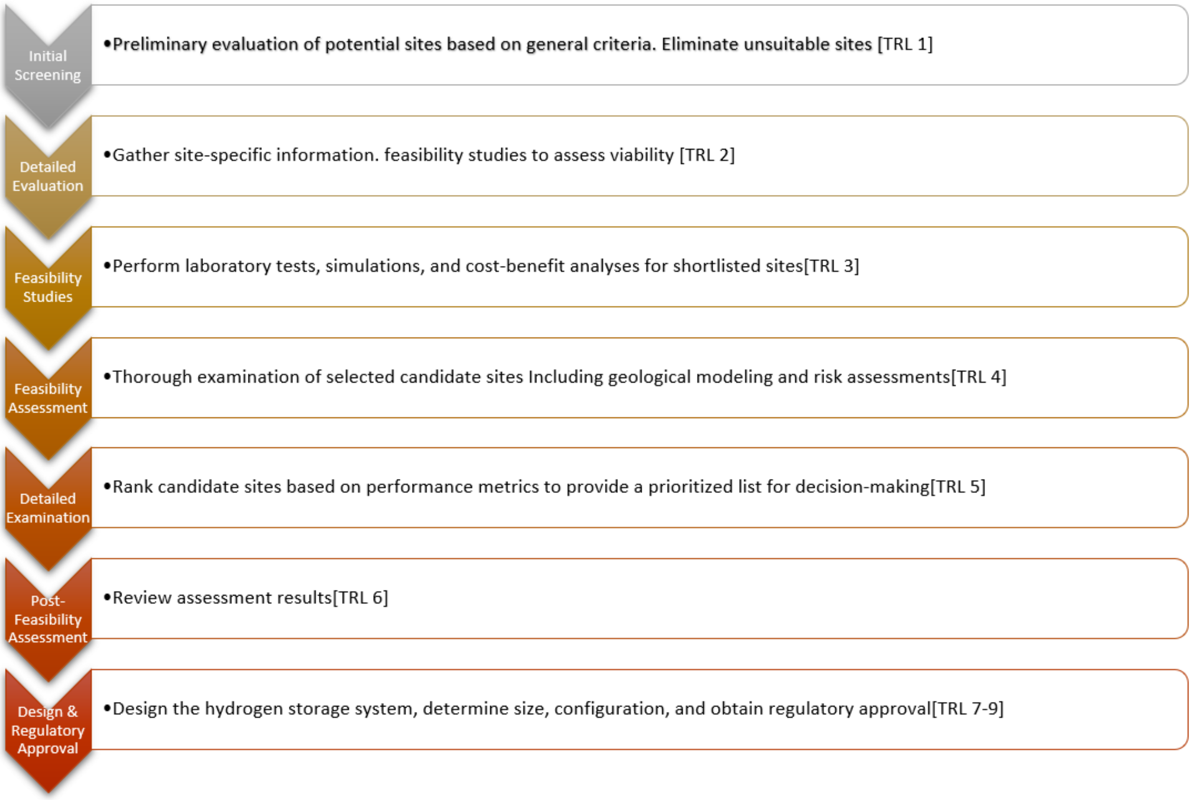
2.1 Pre-feasibility assessment

The initial pre-feasibility assessment phase, corresponding to SRL 1 to SRL 4 in the SRLs framework, relies on readily available data and desktop analysis. This efficient approach helps to eliminate unsuitable options quickly. The primary focus is on geological suitability. Priority is given to porous formations with a proven track record of successful gas storage, such as depleted gas reservoirs and suitable aquifer traps. Additionally, the geological stability of these formations is scrutinized to ensure they meet the necessary criteria for hydrogen storage. Sealing integrity is another critical aspect evaluated during the pre-feasibility assessment. The presence and effectiveness of caprock formations overlying the target reservoir are assessed. Ideally, these caprocks should have low permeability and minimal fracturing to ensure secure hydrogen containment. Regional geological stability is also factored in, avoiding regions with high seismic activity or active faults that could compromise reservoir integrity.

Apart from screening operations performed for classic natural gas storage, such as assessing reservoir performance, flow rates, and the number of wells, an initial reservoir performance assessment is also useful at this stage. This involves creating a simple simulation model to forecast the storage capacity and deliverability of the reservoir. Understanding the rates and volumes that can be delivered is helpful to determine the suitability of a reservoir for hydrogen storage.

Data acquisition and analysis are integral to desk-based screening. Existing datasets from government geological surveys, industry reports, and academic publications are utilized. These datasets include seismic surveys, well logs, core analysis reports, and regional geological maps. Geospatial Information Systems (GIS) play a valuable role in integrating and analyzing various spatial datasets, visualizing, and identifying promising areas based on geological parameters. Clear exclusion criteria are defined to eliminate unsuitable sites, such as shallow formations with a high risk of leakage, the presence of active faults, or proximity to populated areas or environmentally sensitive zones.

In addition to these criteria, the evaluation criteria presented in Deliverable D1.5 of the HyUSPRe project are applied. These criteria include depth, temperature, permeability, porosity, and thickness, formation water salinity, and reservoir complexity. These factors are useful for screening a portfolio of sites into a shortlist of potential candidates, ensuring a comprehensive assessment of each site's suitability for hydrogen storage. A flowchart for decision making process from screening phase to implementation has been created based on the different assessment levels and is shown in Figure 2.



- **Preliminary evaluation of potential sites based on general criteria. Eliminate unsuitable sites** [TRL 1]
- Gather site-specific information. feasibility studies to assess viability [TRL 2]
- Perform laboratory tests, simulations, and cost-benefit analyses for shortlisted sites[TRL 3]
- Thorough examination of selected candidate sites Including geological modeling and risk assessments[TRL 4]
- Rank candidate sites based on performance metrics to provide a prioritized list for decision-making[TRL 5]
- Review assessment results[TRL 6]
- Design the hydrogen storage system, determine size, configuration, and obtain regulatory approval[TRL 7-9]

Figure 2. Step by step decision making process from screening phase to implementation.

2.2 Feasibility assessment

Following the pre-feasibility assessment, shortlisted candidates undergo a feasibility assessment, which aligns with SRL 5 in the SRLs framework. This stage involves a more detailed geological characterization. This stage is beneficial for refining the understanding of the reservoir's suitability and is more intensive and specific than the initial screening.

Exploratory wells are then drilled to gather data on the reservoir's physical properties, including porosity, permeability, and pore-fluid characteristics. The HyUSPRe study primarily focuses on existing gas storages and depleted gas fields, most of which are already well-defined by legacy exploration/appraisal wells. Drilling new exploration wells would be considered only if existing data is deemed insufficient in quality or quantity to perform the necessary evaluations for feasibility and business decisions. Therefore, drilling new wells would be solely case-dependent Core samples retrieved from the wellbore are analyzed in the laboratory to assess the rock's mineralogical composition, potential for geochemical interactions with hydrogen, and overall mechanical stability. Geochemical modeling simulations are also conducted to predict any adverse reactions that could affect hydrogen storage or the integrity of the reservoir formation.

Based on the data gathered from the feasibility assessment, a comprehensive reservoir engineering evaluation is performed. This evaluation focuses on assessing the technical and economic feasibility of hydrogen storage in the shortlisted reservoirs. Reservoir capacity estimation is important, considering factors like porosity, reservoir pressure, geometric factors, and production history and allocation per well, which are indicative of the level of compartmentalization (complexity) and the volume connected to wells, i.e., injectivity per well. Injectivity and deliverability analysis is also conducted, analyzing the hydraulic conductivity of the formation and designing well completion strategies to optimize hydrogen injection and withdrawal processes. A preliminary economic assessment is conducted to evaluate the potential cost-effectiveness of hydrogen storage in the identified reservoir, considering drilling costs, well completion expenses, infrastructure development, and operational costs.

For a detailed step-by-step guide on evaluating hydrogen storage sites, please read Chapter 3 of this report. Chapter 3 provides comprehensive procedures and criteria for site-specific assessments, ensuring a thorough and systematic approach to determining the feasibility and safety of potential hydrogen storage sites.

2.3 Post-feasibility assessment

Assessing the potential environmental and societal impacts of developing a hydrogen storage facility is a key aspect of the post-feasibility assessment, aligning with SRL 6 to SRL 9 in the SRLs framework. This involves conducting an environmental impact assessment (EIA) to evaluate the potential impact of hydrogen storage operations on air quality, water resources, and local ecosystems. The assessment also considers potential mitigation strategies for any identified environmental concerns. Engaging with local communities and relevant stakeholders throughout the screening process fosters transparency and allows for addressing any concerns regarding the project's potential social and economic impacts.

By integrating the findings from all the aforementioned stages, a comprehensive picture of each potential reservoir's suitability for hydrogen storage is established. This allows for a well-informed decision-making process, considering technical feasibility, economic viability, environmental impact, and social acceptance.

Research projects can further refine the decision-making process by incorporating additional considerations specific to hydrogen storage, such as microbial community analysis. Evaluating the indigenous microbial communities present within the reservoir formation can help understand their potential impact on hydrogen storage through biogeochemical processes. This comprehensive approach ensures that all relevant factors are considered, leading to a robust and sustainable hydrogen storage solution.

3 Detailed procedures for evaluating hydrogen storage sites

In the previous chapter, we provided an overview of the structured stages involved in the decision-making process for assessing reservoir and site suitability for hydrogen storage. Building on this foundation, this chapter details the steps for site-specific assessment. This comprehensive guide encompasses the stages of detailed evaluation, feasibility studies, and feasibility assessment. It provides guidelines on the specific studies to conduct and the methodologies to employ, ensuring a thorough evaluation of potential hydrogen storage sites.

The site-specific assessment process is helpful for confirming the suitability of a selected site for hydrogen storage. This involves a more intensive and detailed examination than the initial screening and pre-feasibility assessment stages. By following these detailed procedures, project managers, engineers, and decision-makers can systematically evaluate and verify the technical, economic, and environmental viability of potential hydrogen storage sites.

3.1 Geochemical reactions in hydrogen storage

3.1.1 Introduction

During hydrogen storage in porous reservoir rocks geochemical reactions can occur due to hydrogen's role as an electron donor. These reactions are influenced by the mineral composition of the reservoir rock, the acidity and composition of the formation water (brine), the presence of residual gases such as methane, nitrogen, and CO_2, and the reservoir temperature and pressure. For example, hydrogen can drive the reduction of minerals like pyrite, generating hydrogen sulfide (H_2S), and can also reduce electron acceptors such as sulfates, carbonates, and iron oxides [2]. These geochemical changes can affect the reservoir's porosity, permeability, and overall integrity, influencing the feasibility and safety of hydrogen storage projects [3], [4].

3.1.2 Impact: why this is necessary

Understanding and quantifying the potential geochemical reactions that hydrogen can induce in reservoir rocks is beneficial for assessing the risks and feasibility of hydrogen storage. These reactions can alter the physical and chemical properties of the reservoir, impacting its suitability for long-term hydrogen storage. By studying and measuring the rates at which these reactions occur, we can develop parameterizations to use in models for site-specific studies. This enables the development of strategies to mitigate adverse effects and enhance the safety and effectiveness of hydrogen storage in geological formations [5].

3.1.3 Methodology: experiments for assessing geochemical reactions

The geochemical research undertaken during HyUSPRe at UEDIN and TNO aimed to provide insights into the risk of geochemical reactions during hydrogen storage. Experiments were conducted to determine the hydrogen/rock/formation fluid reactions and their dependence on temperature, pressure, and acidity. The potential for H_2S generation from the reduction of pyrite, pore space reduction, geomechanical changes, caprock integrity loss, and the impact of methane and CO2 on the hydrogen/brine/rock system were also studied.

Experiments [6], [7], [8] were carried out in 185 ml, Ni and Cr rich stainless-steel alloy autoclave reactors with Dursan coating or a Teflon liner, capable of withstanding temperatures up to 150°C and pressures up to 350 bars. Pure gases, including nitrogen, hydrogen, and hydrogen sulphide, were supplied by Air Products to ensure high experimental accuracy. Key strategies included disaggregating samples to enhance reaction surface area, sterilizing samples to eliminate biological reactions, continuously stirring samples, creating an anoxic environment, controlling hydrogen partial pressure, maintaining temperature, and conducting control experiments with nitrogen. Analytical techniques used included gas chromatography-mass spectrometry (GC-MS), pH electrode, X-ray diffraction spectroscopy (XRD) with Rietveld refinement, and Scanning Electron Microscopy (SEM) equipped with Energy Dispersive Spectroscopy (EDX). These methods ensured a comprehensive analysis of the chemical and structural changes during the experiments. The experiments covered a broad range of temperatures (313.15 to 423.15 K), pressures (1 to 20 MPa), and solution salinities (0 to 250 ppt NaCl) to replicate the in-situ environment of potential hydrogen storage sites.

By following this methodology, future studies can ensure a thorough understanding of the geochemical reactions and their impacts on hydrogen storage. A summary of the WP2 experiments can be found in Table 2, which can serve as a reference for designing similar experiments for other reservoirs.

3.1.4. Lessons learned and decision-making process

Several key lessons were learned from the experiments. Ensuring samples were prepared in an anoxic environment and sterilized to exclude biological reactions was a part of process. Continuous monitoring of fluid sampling, pressure, and temperature using high-precision instruments provided accurate data. Utilizing advanced analytical techniques for fluid and solid sample examination before and after experiments ensured detailed investigation of geochemical interactions.

Best practices included collecting samples under anaerobic conditions, sterilizing them, and using high-precision instruments for monitoring and analysis. Safety protocols were strictly adhered to, especially when handling hydrogen or hydrogen sulphide gas, to mitigate risks associated with embrittlement, corrosion, explosions, and toxicity. Implementing leak detection systems and using materials and equipment rated for high-pressure and temperature environments ensured experimental integrity and safety.

Using the experimental data obtained, we could develop parameterizations of the reactions, and by incorporating these into geochemical models, we could quantify the effects of the reactions, leading to improved understanding of the potential risks associated with geochemical reactions during hydrogen storage in geological formations.

To ensure a thorough suitability assessment, it is helpful to conduct detailed geochemical studies before the implementation stage. These studies provide a comprehensive understanding of the geochemical interactions between hydrogen, reservoir rocks, and formation fluids. By quantifying these interactions, we can develop accurate models and effective strategies for safe and efficient hydrogen storage.

3.2 Microbial metabolisms in hydrogen storage

3.2.1 Introduction

During hydrogen storage in porous reservoir rocks, three main microbial processes can occur, for which hydrogen serves as an electron donor. These processes are sulfate reduction, methanogenesis, and acetogenesis. The reaction equations for these processes are as follows:

- Sulfate reduction: $4H_2+SO_2+H+\rightarrow HS-+4H_2O$
- Methanogenesis: $4H_2+CO_2\rightarrow CH_4+2H_2O$
- Acetogenesis: $4H_2+2CO_2\rightarrow CH_3COOH+2H_2O$

Understanding these microbial processes is useful for assessing the impact of microbial activity on hydrogen storage [9].

3.2.2. Impact: why this is necessary

The presence and activity of microbes in reservoir rocks can significantly influence hydrogen storage projects. Microbial metabolisms such as sulfate reduction, methanogenesis, and acetogenesis can lead to the consumption of stored hydrogen and the production of reaction products like hydrogen sulfide (H_2S) that may affect the integrity and safety of hydrogen storage. Therefore, evaluating microbial activity and its potential impacts is useful for the effective and safe implementation of hydrogen storage in geological formations [10], [11].

3.2.3. Methodology: experiments for evaluating microbial metabolisms

The microbial studies in HyUSPRe conducted at WUR (Wageningen University Research) aimed to understand the microbiological impact on subsurface hydrogen storage. Laboratory-scale cultivations were conducted using in-situ reservoir fluids both with and without rock samples, to track microbial activities of sulfate reduction, methanogenesis, and acetogenesis. Data on microbial growth and metabolic activity were collected to determine kinetic parameters, which were then integrated into simulation models for field simulation extrapolation.

Proper protocols such as sterilization of equipment, use of anaerobic chambers, and adherence to aseptic techniques were followed for sample collection to minimize contamination and maintain sample integrity. Samples were taken for microbial community analysis, chemical analysis, and incubation studies to assess microbial risk comprehensively. For molecular analysis, liquid brine samples were filtered and stored frozen for microbial community determination via amplicon sequencing. Chemical analysis focused on Cl^- and $SO4^{2-}$ concentrations using ion exchange chromatography (IC). Incubation studies were conducted under anaerobic conditions, simulating reservoir conditions with high-pressure and temperature reactors.

Reservoir samples were tested under conditions simulating hydrogen storage, with some scenarios including 80% H_2 / 20% CO_2 headspace and added nutrients to enhance microbial activity. Monitoring included pH, temperature, and pressure within the reactor, with sterile controls performed in parallel. Microbial growth was monitored by quantifying cell numbers using qPCR or dPCR targeting group-specific genes. Gas chromatography (GC) measured hydrogen and methane concentrations, while ion exchange chromatography (IC) and calorimetric methods quantified sulfate and hydrogen sulfide concentrations, respectively. High-Performance Liquid Chromatography (HPLC) was used to determine acetate and other volatile fatty acids concentrations.

These experiments, conducted during the HyUSPRe project, provided valuable insights into the microbial risks associated with hydrogen storage. However, similar methodologies should be applied to other reservoirs under consideration for hydrogen storage. By replicating these studies, we can comprehensively assess the suitability of different reservoirs for hydrogen storage, ensuring safe and effective implementation. This approach is not limited to HyUSPRe but is applicable to any reservoir being evaluated for subsurface hydrogen storage, providing a robust framework for understanding and mitigating microbial risks.

3.2.4. Lessons learned and decision-making process

From the experiments, several important lessons were learned. Ensuring samples were collected and stored anaerobically was important to maintaining sample integrity and accurately simulating subsurface conditions. Continuous monitoring of microbial growth, substrate consumption, and product formation provided valuable data for determining kinetic parameters. Adhering to safety protocols when handling samples and conducting experiments minimized contamination and ensured reliable results.

These findings were integrated into comprehensive site assessments for hydrogen storage feasibility. Best practices included ensuring proper sample collection with easy to follow procedures and instructions, continuous monitoring, and utilizing advanced analytical techniques.

Incorporating these findings into biogeochemical models provided insights into microbial processes and their impact on hydrogen storage.

Initial and periodic sampling and analysis during the site assessment phase are recommended to evaluate the potential impact of microbial communities and their metabolic activities. This proactive approach helps to identify any microbiological risks early in the evaluation process, allowing for the adaptation of strategies to ensure the safe and effective operation of hydrogen storage sites.

3.3 Flow behaviour of hydrogen in storage reservoirs

3.3.1. Introduction

The flow behavior of hydrogen in the rock layers of a pore storage facility may differ from that of natural gas due to hydrogen's unique properties, such as compressibility, density, and viscosity. Additionally, interactions with residual or cushion gases, liquid phases (water, oil), and the rock matrix must be considered. Understanding these differences is important for effective hydrogen storage [12], [13].

3.3.2. Impact: why this is necessary

To assess the flow behavior of hydrogen, it is important to conduct site-specific investigations or compile relevant data from literature. These investigations help understand how hydrogen's properties influence its behavior under subsurface storage conditions, ensuring safe and efficient storage. Factors like compressibility, density, viscosity, interfacial tension, relative permeability, capillary pressure, solubility, diffusivity, and mechanical dispersivity need to be examined to predict hydrogen's flow characteristics accurately [14], [15], [16].

3.3.3. Methodology: experiments for evaluating flow behaviour

The compressibility, density, and viscosity of hydrogen or a hydrogen-rich gas mixture under expected pressure and temperature conditions can be determined using high-pressure cells (e.g., PVT cells) and long capillaries for viscosity measurements. The interfacial tension between hydrogen and reservoir brine, and the brine contact angle in the rock-brine-hydrogen system, are measured using high-pressure view cells with various methods such as captive bubble, pendent drop, or tilted plate.

Relative permeability and capillary pressure curves are useful for understanding the rock-brine-hydrogen system under storage conditions. These can be measured using core flooding setups under steady-state or dynamic conditions, with methods like the porous plate technique for capillary pressure. The solubility of hydrogen in reservoir brine is determined using stirred high-pressure autoclaves, where brine and hydrogen reach thermodynamic equilibrium under specific conditions. Effective gas-gas diffusivity and mechanical dispersivity are measured using diffusion cells and core flooding systems or slim tube devices, respectively.

The HyUSPRe project conducted various experiments related to storage sites in Europe. Measurements for hydrogen-methane diffusion were carried out with different reservoir rock samples at pressures up to 287 bar and temperatures up to 107°C. The effective diffusion coefficients showed high variance, influenced by porosity and permeability. A correlation was developed to estimate the diffusion coefficient based on these parameters.

The project also investigated the influence of pressure, temperature, and flow velocity on hydrogen-methane dispersivity. Results indicated a strong dependence on pressure and fluid properties. Relative permeability measurements under dynamic conditions showed that pore structure and porosity significantly influence hydrogen's relative permeability, with higher porosity leading to higher permeability. Salinity was found to impact relative permeability, with higher salinity resulting in lower hydrogen permeability.

Experiments conducted for the flow behavior studies can be found in Table 3. This table can serve as a reference for designing similar experiments for other reservoirs.

3.3.4. Lessons learned and decision-making process

Key lessons learned from the experiments include the importance of using larger diameter and longer core samples for relative permeability measurements to better represent upscaling effects and minimize capillary end-effects. Continuous monitoring by fluid sampling, pressure, and temperature using high-precision instruments provided accurate data. Safety protocols, especially when handling high-pressure gases, ensured reliable results.

Best practices developed from these studies highlight the need to combine experimental investigations with simulation studies. Simulation aspects to consider include viscous fingering, gravity override during UHS development in aquifers, displacement and mixing with residual gas in depleted reservoirs, and gravity segregation effects due to hydrogen's low density. These practices aim to provide a comprehensive understanding of hydrogen's flow behavior in storage reservoirs, which is helpful for the development of effective hydrogen storage strategies.

3.4 Durability and integrity of critical elements in hydrogen storage

3.4.1. Introduction

The durability and integrity of critical elements in porous reservoir storage systems determine the long-term safety and reliability of underground hydrogen storage operations. These critical elements include the storage reservoir, the caprock, faults, the well system, and the surface facilities. For instance, cyclic hydrogen injection and withdrawal over the lifespan of UHS projects could lead to progressive damage (inelastic deformation) of the reservoir near the well area or accelerated corrosion and mechanical damage to well systems. These processes increase risks associated with reduced reservoir injectivity and productivity or loss of well integrity [17].

3.4.2. Impact: why this is necessary

When considering hydrogen storage projects compared to seasonal storage of natural gas, cyclic injection and withdrawal of hydrogen-containing gas streams may pose higher durability and integrity risks. These risks stem from the frequent stress changes caused by pressure and temperature variations, as well as the potential reactions between hydrogen and the materials in the rock or wells. It is beneficial to incorporate risk mitigation measures into project planning to manage these risks effectively. Identifying and comprehending these risks are noticeable for developing guidelines that prioritize the safety and efficiency of hydrogen storage projects, particularly considering the increased number of cycles per year [18], [19].

3.4.3. Methodology: experiments for assessing durability and integrity of critical elements

Experiments in WP5 focused on obtaining data to assess risks associated with well integrity, reduced injectivity/productivity, and breach of geological seals. Samples of well cement, reservoir rocks, caprocks, and scaled-down well systems were tested under various conditions to understand how hydrogen affects these materials.

Well cement samples were exposed to nitrogen and hydrogen under controlled conditions, and their mechanical properties were measured using unconfined compressive strength (UCS) and cyclic axial stress tests. The results indicated that the changes in the elastic properties and strength of the cement due to hydrogen exposure were minor compared to those observed with nitrogen exposure, although no major effects on mechanical properties were observed within the tested timescales.

Reservoir and caprock samples from sites in the Netherlands and Italy were subjected to triaxial tests to study the interaction between hydrogen and rock materials under confined pressure. The tests showed limited effects on rock properties, such as slight changes in Young's modulus and permeability due to cyclic stress changes, similar to those observed with nitrogen. However, these changes emphasize the need for further investigation under various conditions and reservoir types to fully understand the long-term impacts.

Scaled-down well system experiments simulated the effects of cyclic pressure changes due to hydrogen injection and withdrawal. These tests provided data on the interface properties of well systems, poro-elastic effects, and along-well flow properties. Initial results indicated limited effects on system performance after multiple cycles, but further evaluation and data processing are needed.

A summary of experiments in WP5 to assess durability and integrity of rock and well materials can be found in Table 4.

3.4.4. Lessons learned and decision-making process

Key lessons from the experiments include the importance of understanding the interaction between cyclic stress changes and hydrogen exposure on reservoir and well materials. Continuous monitoring of mechanical properties, permeability, and elastic properties under various conditions provided valuable data for assessing risks.

To improve the decision-making process for reservoir and site suitability assessments for hydrogen storage, integrating a risk management plan is functional. The following recommendations are based on the experimental findings:

1. Screen wells (in case of re-use) to assess well integrity risks.
2. Conduct mechanical characterization of the reservoir to assess the likelihood of cumulative inelastic deformation in the near-well area, which can lead to long-term injectivity/productivity risks. Simple UCS tests can provide initial indications.
3. Perform a model analysis of the spatial and temporal evolution of stresses in the UHS complex to assess containment risks, such as caprock fracturing and fault reactivation.

These practices aim to ensure a comprehensive understanding of the durability and integrity of critical elements in hydrogen storage, contributing to the development of effective and safe hydrogen storage strategies. The experimental data serve as input parameters for models that provide forecasts of risks for actual UHS operations, thereby enhancing the overall safety and efficiency of hydrogen storage projects.

3.5 Scoping integrated modeling studies

3.5.1. Introduction

In underground hydrogen storage operations, numerical models play a critical role in predicting and optimizing processes. By developing and calibrating models based on subsurface processes, the storage operation can be enhanced. It is important to understand these processes across different scales, from laboratory to field scale, to ensure accuracy and reliability in predictions.

3.5.2. Impact: why this is necessary

Numerical simulations help translate laboratory findings to field-scale applications, allowing for better planning and risk assessment in UHS projects. These simulations are practical for understanding complex interactions within the storage reservoir, predicting gas flow behavior, and optimizing storage operations.

3.5.3. Methodology: lessons learned from the simulation studies

The HyUSPRe project conducted various laboratory experiments investigating hydrodynamics and bio- and geochemical reactions. These experiments were largely replicated in numerical simulations, matching observations to validate the models. A key outcome was the development of a correlation for binary diffusion coefficients based on petrophysical properties, pressure, and temperature, which is applicable across a wide range of storage conditions.

Microbial growth experiments in batch reactors allowed calibration of reaction kinetics, focusing on parameters such as maximum growth rate and yield factor. However, the dynamics of microbial growth in porous media remain a research target. Similarly, geochemical reaction experiments, such as the pyrite-to-pyrrhotite reduction, were successfully reproduced with a new kinetic reaction model.

One of the significant challenges is the upscaling from laboratory to field scale. Verification through core sample experiments and field observations is required to enhance model predictability. Field-scale simulations in HyUSPRe modeled multiphase multicomponent transport processes during storage operations at three specific sites using actual field data. These simulations highlighted the importance of gas-gas mixing and temporary hydrogen loss, especially at the beginning of UHS operations. Introducing an initial hydrogen concentration helps stabilize fluctuations numerically. The simulations indicate a hydrogen accumulation at the reservoir crest due to gravity differences, which should be considered during well selection. However, it is important to note that this phenomenon has only been observed in models and has not been verified through experiments or pilot projects. Long-term hydrogen losses are primarily due to bio- and geochemical reactions, with reaction products like hydrogen sulfide appearing in the withdrawal stream. Limiting reactant supplies, such as carbon dioxide, can mitigate these reactions.

3.5.4. Relevant functions and selection of simulator

Choosing the appropriate simulation tool, including its models and functions, is fundamental for accurate predictions. Open-source solutions, such as DuMu^x, demonstrated high flexibility for modeling molecular diffusion and bio- and geochemical reactions. DuMu^x's consistent implementation of transport and fluid models allowed for simultaneous laboratory and field-scale simulations. Proprietary software like COMSOL Multiphysics also showed potential for laboratory-scale modeling [20], [21].

For reservoir-scale simulations, proprietary reservoir simulators are commonly used for optimizing natural gas storage operations. These typically use modified black oil models for general parameters, but compositional models are necessary for accurate prediction of gas mixing and hydrogen concentrations in the withdrawal stream. UHS in aquifers with hydrogen as cushion gas can be sufficiently modeled with black oil models.

The HyUSPRe project assessed DuMu^x [22] CMG-GEM [23] and COMSOL Multiphysics [24] for field-scale applications. DuMu^x and CMG GEM provided congruent results regarding transport and bio-reactive implementations, while COMSOL Multiphysics did not demonstrate any effectiveness for large-scale scenarios. CMG GEM offers a balance of user-friendliness, computational cost, and accuracy, whereas DuMu^x allows for more complex transport models. Proprietary software is suitable for broader applications, while open-source tools are advantageous for specific reactions and smaller field tests [25] (Table 1).

Table 1: Overview of the different features of the individual models.

Model / Prediction of	Black oil model	Compositional	Compositional incl. chemical reactions
Pressure development	x	x	x
Gas-water displacement	(x)[1]	x	x
Gas-gas mixing (spatial distribution of H_2 and withdrawal gas compositions)	(x)[1]	x	x
Biochemical reactions			x
Geochemical reactions			x

[1] sufficient for aquifer storage with H_2 as cushion gas

4 Final remarks

The HyUSPRe project has comprehensively evaluated the feasibility and potential of underground hydrogen storage in porous reservoirs in Europe. The insights gathered from this project provide a strong foundation for implementing UHS technologies, emphasizing the importance of detailed geochemical, microbial, flow, and geomechanical analyses to ensure safe and efficient hydrogen storage.

Key findings from the report highlight the complex interactions between hydrogen and reservoir materials, the significant role of microbial activities, and the unique flow behaviours of hydrogen compared to other gases. Experimental studies and numerical models have demonstrated the necessity of site-specific assessments to address the variations in geological conditions and reservoir properties.

The guidelines developed offer a structured approach to site selection and implementation, ensuring a thorough evaluation process from initial screening to post-feasibility assessments. This report emphasizes the importance of continuous monitoring, advanced analytical techniques, and comprehensive risk assessments to mitigate potential issues related to geochemical reactions, microbial activities, and the integrity of storage systems.

Looking forward, the report underlines the need for further laboratory research, advancing our predictive modeling capabilities, and pilot projects to validate laboratory and simulation results in real-world conditions. Establishing robust regulatory frameworks and engaging with the public are also some steps towards the successful deployment of UHS technologies.

In conclusion, the HyUSPRe project has provided invaluable guidelines and methodologies that pave the way for the safe and effective implementation of hydrogen storage in porous reservoirs. By adhering to these recommendations, stakeholders can ensure a more resilient and sustainable hydrogen storage infrastructure, supporting the transition to a cleaner energy future.

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Appendix

Table 2 Summary of the WP2 experiments.

Task	**Equipment utilised**	**Rocks tested (anonymized)**	**Temperature range (°C)**	**Pressure range (bar)**	**Brine salinity range (% NaCl)**
Task 2.1: Mineral reactions with hydrogen	Batch reaction vessels	HyUSPRE R1-R5 Pure minerals: quartz, feldspars, calcite, anhydrite, Clashach sandstone, locharbriggs sandsone, Whitton fell sandstone.	80	80 - 200	3.5%
Task 2.2: Potential for hydrogen sulfide generation	Batch reaction vessels	Sedimentary pyrite; Specimen grade pure pyrite; Pyrite/calcite mix	40, 80, 120, 150	30 - 200	3.5 and 8%
Task 2.3: Impact on core permeability and mechanical integrity	Batch reaction vessels, flow though vessel X-ray transparent flow through.	Clashach sst, Locharbriggs sst, HyUSPRe AN#8-9 HyUSPRe FN#89 Bunter sandstone	20, 50	50 – 105	0 – 3.5% hydrogen saturated brine at 3.5% Bunter sandstone equilibrated brine
Task 2.4: Impact on caprock	Batch reaction vessels. Flow through vessel	Kimmeridge clay (east Brae UK North Sea) Rag caprock	80	60	3.5% equilibrated brine
Task 2.5: Impact CH_4 and CO_2		HyUSPRe A12#12 HyUSPRe A12#11 HyUSPRe R1	80	49.3 – 62.8	3.5%

Table 3 Experiments conducted for the flow behaviour studies.

Task	**Equipment utilised**	**Rocks tested (anonymized)**	**Temperature range (ºC)**	**Pressure range (bar)**	**Brine salinity range (% NaCl)**
UEDIN Task 4.3: Relative permeability curves (unsteady state hydrogen-brine relative permeability)	Flow through vessel (1)	Sandstone 1 Sandstone 2 Limestone	60	100, 200	3.5%, 10%, 20%
UEDIN Task 4.3: Relative permeability curves (steady state drainage and imbibition cycles for relative permability)	Flow though vessel (2)	Clashach sandstone Locharbriggs sandstone Whitton fell sandstone. HyUSPRE AN#8-9 HyUSPRe FN#89 HyUSPRe FN#11	60	100	3.5%

Table 4 Summary of experiments in WP5 to assess durability and integrity of rock and well materials.

Task	# tests	Sample type	Exposure	Exposure conditions (P/T)	Test type*	Axial stress (cycle)	Test conditions (P_c / P_p / T)**	Parameter/ property measured***
				[MPa / °C]		[MPa]	[MPa / °C]	
T5.2	2	class G cement	-	-	UCS	-	- / - / room T	ρ, E_s, ν_s, UCS
T5.2	1	class G cement	-	-	cyclic (axial)	4-15 cycling	8 / 1 / room T	ρ, V_p, V_s, E_s, E_d, ν_s, ν_d, US
T5.2	2	class G cement	N_2 30 days	20 / 80	UCS	-	- / room T	ρ, E_s, ν_s, UCS
T5.2	2	class G cement	N_2 60 days	20 / 80	UCS	-	- / room T	ρ, E_s, ν_s, UCS
T5.2	1	class G cement	N_2 60 days	20 / 80	cyclic (axial)	4-15 cycling	8 / 1 / room T	ρ, V_p, V_s, E_s, E_d, ν_s, ν_d, US
T5.2	2	class G cement	H_2 30 days	20 / 80	UCS	-	- / room T	ρ, E_s, ν_s, UCS
T5.2	2	class G cement	H_2 30 days	20 / 80	UCS	-	- / room T	ρ, E_s, ν_s, UCS
T5.2	1	class G cement	H_2 60 days	20 / 80	cyclic (axial)	4-15 cycling	8 / 1 / room T	ρ, V_p, V_s, E_s, E_d, ν_s, ν_d, US
T5.3	1	NAM reservoir	-	-	triaxial	-	2 / 1 / room T 52.6 / 39.3 / 100	ρ, ϕ, V_p, V_s, E_s, E_d, ν_d
T5.3	2	NAM reservoir	N_2 60 days	20 / 100	triaxial cyclic (pore)	-	2 / 1 / room T 52.6 / 39.3 / 100	ρ, ϕ, V_p, V_s, E_s, E_d, ν_d, US
T5.3	2	NAM reservoir	N_2 60 days	20 / 100	triaxial cyclic (pore)	-	2 / 1 / room T 52.6 / 39.3 / 100	ρ, ϕ, V_p, V_s, E_s, E_d, ν_d, US
T5.3	1	NAM caprock	-	-	triaxial	-	2 / 1 / room T 52.6 / 39.3 / 100	ρ, ϕ, V_p, V_s, E_d, ν_d
T5.3	1	NAM caprock	N_2 60 days	20 / 100	triaxial	-	2 / 1 / room T 52.6 / 39.3 / 100	ρ, ϕ, V_p, V_s, E_s, E_d, ν_d, US
T5.3	1	NAM caprock	H_2 60 days	20 / 100	triaxial	-	2 / 1 / room T 52.6 / 39.3 / 100	ρ, ϕ, V_p, V_s, E_d, ν_d
T5.3	1	SNAM reservoir	-	-	triaxial	-	2 / 1 / room T 31.0 / 18.3 / 50	ρ, ϕ, V_p, V_s, E_d, ν_d
T5.3	1	SNAM reservoir	N_2 60 days	14 / 50	triaxial	-	2 / 1 / room T 31.0 / 18.3 / 50	ρ, ϕ, V_p, V_s, E_d, ν_d
T5.3	1	SNAM reservoir	H_2 60 days	14 / 50	triaxial	-	2 / 1 / room T 31.0 / 18.3 / 50	ρ, ϕ, V_p, V_s, E_d, ν_d
T5.3	1	SNAM caprock	-	-	triaxial	-	2 / 1 / room T 31.0 / 18.3 / 50	ρ, ϕ, V_p, V_s, E_d, ν_d
T5.3	1	SNAM caprock	N_2 60 days	14 / 50	triaxial	-	2 / 1 / room T 31.0 / 18.3 / 50	ρ, ϕ, V_p, V_s, E_d, ν_d
T5.3	1	SNAM reservoir	H_2 60 days	14 / 50	triaxial	-	2 / 1 / room T 31.0 / 18.3 / 50	ρ, ϕ, V_p, V_s, E_d, ν_d

Task	# tests	Sample type	Exposure	Exposure conditions (P/T)	Test type*	Axial stress (cycle)	Test conditions (P_c / P_p / T)**	Parameter/ property measured***
				[MPa / °C]		[MPa]	[MPa / °C]	
T5.4	1	SDWS1[!] cement	H_2 235 days	19.5 / 110	cyclic (well) no perfs.	N/A	- / 40 / - 35 / 40 / 100	well stresses Q_a
T5.4	1	SDWS2[!] RW_sst	-	-	cyclic (well) full perfs.	3-15 const. σ	8-40 / 5-25 (cycles) / 20-80	casing/sample expansion, Q_a
T5.4	1	SDWS2[!] RW_sst	N_2 123 days	19.1 / 80	cyclic (well) full perfs.	3-15 const. σ	8-40 / 5-25 (cycles) / 20-80	casing/sample expansion, Q_a
T5.4	1	SDWS2[!] RW_sst	H_2 123 days	18.8 / 80	cyclic (well) full perfs.	3-15 const. σ	8-40 / 5-25 (cycles) / 20-80	casing/sample expansion, Q_a
T5.4	1	SDWS3[!] BH_sst	-	-	cyclic (well) partial perfs.	3-15 const. σ	8-40 / 5-25 (cycles) / 20-80	casing/sample expansion, Q_a
T5.4	1	SDWS4[!] BH_sst	-	-	cyclic (well) no perfs.	3-15 const. σ	8-40 / 5-25 (cycles) / 20-80	casing/sample expansion, Q_a

* UCS- Unconfined compressive strength test; cyclic (axial)- confined tests with cyclic axial stress; cyclic (pore)-confined tests with cyclic pore pressure; triaxial- standard triaxial test at low stress and reservoir conditions; cyclic (well)- cyclic well and/or pore pressure (depending on casing perforations).

** P_c- confining pressure; P_p- pore pressure (well pressure in case of SDWS).

*** ρ- sample bulk density; ϕ- sample porosity, E_s- static Young's modulus; E_d- dynamic Young's modulus; ν_s- static Poisson's ratio; ν_d- dynamic Poisson's ratio; UCS- unconfined compressive strength; US- ultimate strength (confined); V_p- compressional wave velocity (ultrasonic); V_s- shear wave velocity (ultrasonic), Q_a- casing-cement annulus flow rate.

[!] SDWS#- scaled down well sample; #1- type 1, cement sheath between steel cylinders, no perforations casing; #2-4- steel cylinder cemented in hollow cylinder of porous reservoir rock; #2- white porous sandstone, full perforations casing ($P_p = P_w$); #3- Bentheim sandstone (BH_sst), partial perforations casing; #4- Bentheim sandstone (BH_sst), no perforations casing.