Programme

• Welcome, general house-keeping rules, Use of chat

• Introduction Hydrogen TCP by Paul Lucchese (Chair IEA Hydrogen TCP)

• Introduction on TCP-Task42: Objectives, scope, structure

• Subtask presentations
  • Katriona Edlmann: Geochemical and Microbial Processes
  • Sam Xie: Storage Integrity
  • Ed Hough: Storage Performance and Screening
  • Remco Groenenberg: Storage Facilities and Wells
  • Arnaud Reveillere: Economics and System Integration
  • Richard Schultz: Societal Embeddedness of UHS

• General Q&A

• Discussion with participants: priority issues (gaps, risks, etc.), needs, expectations

• Wrap-up and outlook.
Brief Introduction

Presenter: Paul Lucchese,
French Alternative Energies and Atomic Energy Commission

Chair Hydrogen TCP
Introduction to the Hydrogen TCP
In a nutshell

Members
25 Member Countries
+ European Commission
8 Sponsors

Tasks
7 Open
40 Finished
≥ 5 in definition

Experts involved
In collaborative research on hydrogen and hydrogen technologies

Experts involved
250+

Members
33

Tasks
40+

Experts involved
250+
Tasks

Main Hydrogen TCP activities
Task portfolio status

- Innovation for H₂ transport
- International H₂ Supply Chains – models and cost analysis
- H₂ LCA, societal and environmental impact

- H₂ for Marine Applications + Ports
- Natural H₂
- Roadmaps for the use of H₂ in Industry
- H₂ in Islands
- H₂ in the Mining, Mineral Processing, and Resource Sectors

- Preliminary Idea
- Project Definition Phase
- Kick-off
- Active
- Closing Steps
- End

- Task 40 – Energy Storage and Conversion
- Task 42 – Underground H₂ Storage
- Task 43 – Safety and RCS of Large Scale H₂ Energy Applications
- Task 44 – HYNE
- Task 45 – Renewable H₂ Production
- Task 46 – Off-shore H₂ Production
- Task 47 – H₂ Certification
- Task 37 – H₂ Safety
- Task 38 – PtH & HtX
- Task 39 – H₂ in the Maritime
- Task 41 – Analysis and Modelling of H₂ Technologies

October 2023

Innovation for H₂ transport

Natural H₂

Roadmaps for the use of H₂ in Industry
Collaboration

Joint activities with entities within the IEA Network and external
Collaboration within the IEA Network
Collaboration with other organizations
Some examples of our collaboration: workshops and events
Thank You!

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1ª Planta Izda.
28760 Tres Cantos, Madrid, Spain
Introduction to
TCP-Task42

Presenter: Serge van Gessel,
TNO – Geological Survey of the Netherlands

Coordinator TCP-Task42

Technology Collaboration Programme
by led
**TCP TASK 42**

**Underground Hydrogen Storage**

58 participating organizations

- Industry
- Universities
- Research Institutes
- Governmental

**Start 2022**

**Ending in December 2024**

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<table>
<thead>
<tr>
<th>Europe</th>
</tr>
</thead>
</table>
| **Netherlands** | TNO - Netherlands Organisation for Applied Scientific Research
| Delft University of Technology
| University of Utrecht
| EBN - Energie Beter Nederland
| N.V. Nederlandse Gasunie
| Shell International Research Institute of the Netherlands
| Wageningen University & Research
| SocMin - State Supervision of Mines and Geology |
| **Spain** | Trinity Energy Storage
| Fundación del Hidrógeno en Aragón
| CHN2 - Centro Nacional del Hidrógeno
| Repsol
| Enagas |
| **Portugal** | PERN - Redes Energéticas Nacionais
| **France** | Geostock
| University of Grenoble - Alps |
| **Italy** | ENI
| University of Turin
| PSE S.p.A. - Ricerca sul Sistema Energetico |
| **Germany** | Helmholtz Centre Potsdam, GFZ
| Ruhr-University Bochum
| DBi Gas- und Umwelttechnik GmbH
| Storage-Exel GmbH
| Technical University Bergakademie Freiberg
| BGR |
| **Austria** | RAG Austria AG
| OMV Austria E&P GmbH |
| **Norway** | NORCE Norwegian Research Centre AS
| University of Bergen
| IE – 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 |

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**CAN**

- University of Toronto

**US**

- DOE - United States Department of Energy
- GTI Energy
- Orion Geomechanics LLC

**Argentina**

- Mychico S.A.

**Australia**

- Woodside Energy
- University of Adelaide
- Curtin University
- Loghard Energy

**New Zealand**

- University of Auckland
- University of Canterbury

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*World map source: samplemaps.com*

**Thursday 12th October 2023 – TCP-Task42- UHS External Stakeholder Webinar**
Establishing the DNA for safe and responsible demonstration and implementation of Underground Hydrogen Storage
UHS targets reservoirs similar to those deployed for UGS. The screening criteria and performance will differ for UHS.

Integrate experiences from demonstration in multiple geological and operational settings

Determine optimal geological and operational conditions

Quantify coupled processes, validation

Monitoring/sampling strategies, standards, norms

Thursday 12th October 2023 – TCP-Task42- UHS External Stakeholder Webinar
Estimated Technical Readiness Levels
Long (10+ year) lead times towards commercial; Capacities needed after 2030

- **Initial idea**
  - Basic principles have been defined

- **Application formulated**
  - Concept and application of solution have been formulated

- **Concept needs validation**
  - Solution needs to be prototyped and applied

- **Early prototype**
  - Prototype proven in test conditions

- **Large prototype**
  - Components proven in conditions to be deployed
  - **Full prototype at scale**
    - Prototype proven at scale in conditions to be deployed

- **Pre-commercial demonstration**
  - Solution working in expected conditions
  - **First of a kind commercial**
    - Commercial demonstration, full scale deployment in final form

- **Commercial operation in relevant environment**
  - Solution is commercially available, needs evolutionary improvement to stay competitive

- **Integration needed at scale**
  - Solution is commercial and competitive but needs further integration efforts

- **Proof of stability reached**
  - Predictable growth

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**Salt Caverns**
- Pure

**Gas fields**
- Fast cyclic - Energy system
- Blended

**Aquifers**
- Pure

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Thursday 12th October 2023 – TCP-Task42- UHS External Stakeholder Webinar
Main challenges for development of Underground Hydrogen Storage

Subtask F: Societal Embeddedness of UHS

Subtask E: Economics and System Integration

Subtask D: Facilities and Wells

Subtask A: Geochemical and Microbial Impacts
Subtask B: Storage Integrity
Subtask C: Storage Performance and Screening

Thursday 12th October 2023 – TCP-Task42- UHS External Stakeholder Webinar
Pilot and Demonstration Projects: Prefeasibility, FEED and Testing

Overview of UHS demo projects and site feasibility studies

- Cavern Plan/Feas.
- Porous Plan/Feas.
- Cavern Operational
- Porous Operational
- Cavern Towngas
- Porous Towngas
- Porous tested

Graph is based on overviews from GIE 2022 and various other sources.
Pathways to de-risking

- Increase the technological confidence in UHS with laboratory experiments, models and subsurface pilots in multiple geological environments and operational settings

- Develop a market for UHS, reduce investment risks for early projects, and resolve knowledge gaps for the UHS business case

- Improve and validate methods and strategies for risk assessment and monitoring

- Assess and establish the conditions for societal embeddedness of underground hydrogen storage in the early stages of research and development
## Subtasks and presentations

**Presenter: Katriona Edlmann (University of Edinburgh)**

**Subtask A:** Geochemical and Microbial Impacts  
- Geochemical processes  
- Microbial processes  
- Hydrogen quality & losses  
- Impacts on Integrity & Performance

**Presenter: Sam Xie (Curtin University)**

**Subtask B:** Storage Integrity  
- Gas Tightness  
- Caprock Integrity  
- Reservoir Integrity  
- Faults and Fractures

**Presenter: Ed Hough (British Geological Survey)**

**Subtask C:** Storage Performance and Screening  
- Hydrogen Flow  
- Physics & Thermodynamics  
- Hydrogen Recovery  
- Cushion Gas Effects

**Presenter: Remco Groenenberg (TNO)**

**Subtask D:** Facilities and Wells  
- Well design & materials  
- Facility design & engineering  
- Operational parameters & limits  
- HSE and monitoring

**Presenter: Arnaud Reveilere (Geostock)**

**Subtask E:** Economics and System Integration  
- CAPEX & OPEX  
- Revenue models  
- Energy system services  
- Market

**Presenter: Richard Schultz (Orion Geomechanics)**

**Subtask F:** Societal Embeddedness of UHS  
- Safety & Environmental impacts  
- Stakeholder involvement  
- Policy, regulations, planning  
- Financial resources, cost/benefit
Subtask A

GEOCHEMICAL AND MICROBIAL PROCESSES

Presenter: KATRIONA EDLMANN, The University of Edinburgh

Lead Subtask-A

- Geochemical processes
- Microbial processes
- Impacts on development and operations
Hydrogen can promote geochemical reactions between storage rocks, formation/sump fluids and the stored hydrogen. Hydrogen is an electron donor for a variety of microbial processes.

Geochemical reactions:
1. Carbonate minerals – reduced to CH₄/CO₂
2. Sulphate minerals – SO₄ reduced to generate H₂S
3. Sulphide minerals (Pyrite) reduction into H₂S
4. Iron oxides reduced to insoluble Fe²⁺
5. Alteration of clay structures
6. Nitrate reduction to ammonia

Microbial reactions:
1. Methanogens consume hydrogen to generate CH₄
2. Iron reducing bacteria transform Fe³⁺ into insoluble Fe²⁺
3. Sulphur species reducing bacteria generate H₂S
4. Acetogens consume hydrogen to produce acetate

Consequences
- Storage integrity Subtask B
- Storage efficiency Subtask C
- Well integrity Subtask D
- Economic integrity Subtask E
- Societal integrity Subtask F
Summary of Key findings: Geochemical reactions

- Currently experimental, modelling and field investigations of geochemical hydrogen reactions during hydrogen storage in porous rocks, salt caverns and lined rock caverns are somewhat limited.
  - Published data is often under conditions that are not representative 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.
  - Most geochemical reactions are kinetically limited, however the reductive dissolution of iron oxides and reduction of pyrite, leading to the formation of hydrogen sulphide are of concern, particularly at temperatures above 100 °C.
Summary of Key findings: Microbial activity

• Currently experimental, modelling and field investigations of microbial activity during underground hydrogen storage are limited.

  • Most field experience of microbial reactivity during UHS is with hydrogen mixtures that contain reactive gasses such as CO₂, rather than 100% hydrogen.

• The available evidence indicates that there is a risk of microbial consumption of hydrogen, gas composition changes, biofilm formation 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.

References:
# Impacts on development and operations

<table>
<thead>
<tr>
<th>Hazard or adverse effect</th>
<th>Description</th>
<th>Possible mitigation</th>
<th>Type of risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas mixture change</td>
<td>Microbial activity can lead to a decrease of hydrogen, increase of H$_2$S or methane, and increase/decrease of CO$_2$</td>
<td>Biocides, Site selection</td>
<td>Technical, safety, economic</td>
</tr>
<tr>
<td>Souring and H$_2$S formation</td>
<td>Microbial activity can lead to H$_2$S formation, a toxic and corrosive gas. Sulphate needs to be present. Enhanced by the presence of hydrogen and easily degradable carbon sources.</td>
<td>Biocides, nitrate, Site selection</td>
<td>Technical, safety, economic</td>
</tr>
<tr>
<td>Steel corrosion</td>
<td>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))</td>
<td>Biocides, coatings, cathodic protection</td>
<td>Technical, economic</td>
</tr>
<tr>
<td>Microbial- induced plugging</td>
<td>Microbial growth will lead to biofilm formation which can cause clogging. Also, mineral plugging can occur upon microbiologically mediated reactions.</td>
<td>Biocides, Site selection</td>
<td>Technical, economic</td>
</tr>
<tr>
<td>Dissolution of minerals and change in reservoir properties</td>
<td>Microbial or chemical reactions can lead to the dissolution of reservoir minerals, e.g., carbonate and other easily dissolvable minerals.</td>
<td>Biocides, Site selection</td>
<td>Technical, safety</td>
</tr>
<tr>
<td>Hydrogen leakage</td>
<td>Hydrogen leakage from reservoirs into the groundwater will affect groundwater microbial communities and associated nutrient cycles.</td>
<td>Leakage prevention</td>
<td>Technical safety</td>
</tr>
</tbody>
</table>
**Summary of key recommendations: Geochemical reactions**

- Scarcity of experimental data, lack of benchmarked models, limited field studies and shortage of publicly available information from commercial hydrogen storage sites uncertainty means that the risk from geochemical and microbial processes remain a technical barrier to the development of underground hydrogen storage. To reduce this uncertainty, the recommendations include:

  1. **More experiments**
     - Improved knowledge of pure mineral kinetic reaction rates with hydrogen at representative conditions.
     - Investigation of fully coupled systems that are more representative of UHS.
     - Assessment of the dynamic impacts of potential geochemical reactions on reservoir permeability and mechanical integrity of reservoir / sealing rocks over time.
     - Improved understanding of the kinetics of hydrogen dissolution.

  2. **Pilot field studies**
     - Improved understanding of potential contaminants in the hydrogen production stream.
     - Standardised methodologies to compare across laboratory and modelling studies.
     - Field data for validation of laboratory and modelling outputs.

To reduce the uncertainty surrounding geochemical reactivity, the key recommendations are:

1. **More experiments**
   - under representative storage conditions.
2. **Pilot field studies** to provide validation to the laboratory and modeling studies.
Summary of key recommendations: Microbial activity

To reduce the uncertainty surrounding microbial activity, the key recommendations are:

1. **More experiments** under representative storage conditions.

2. **Pilot field studies** to provide validation to the laboratory and modeling studies.

- There is a recognised 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. Some key knowledge gaps for an improved understanding of the microbial activity include:

<table>
<thead>
<tr>
<th></th>
<th>Improved microbial reactivity rates and growth constraints based on microbial experiments using representative conditions of UHS</th>
<th>Understanding of the evolution and competition between microbial communities during the lifetime of UHS sites.</th>
<th>Understanding the interplay between geochemical and microbial reactions and nutrient availability.</th>
<th>Thermodynamic data for microbial reactions to improve the modelling for long-term site management.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porous rocks only:</td>
<td>Experiments to establish the influence of microbial activity on flow.</td>
<td>Standardised methodologies for laboratory experiments and for field sampling.</td>
<td>Field data for validation of laboratory and modelling outputs</td>
<td>Field sites for testing/developing of monitoring and mitigation technologies.</td>
</tr>
</tbody>
</table>

Thursday 12th October 2023 – TCP-Task42- UHS External Stakeholder Webinar
# Summary of findings and recommendations

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

<table>
<thead>
<tr>
<th><strong>Constraining and preventing reactions</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>• Databases of geochemical and microbial information with a standardised approach.</td>
</tr>
<tr>
<td>• Determine optimum geological and operational conditions for site screening.</td>
</tr>
<tr>
<td>• Quantify coupled processes in dynamic subsurface environment.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Monitoring of hydrogen reactions</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>• Improve the understanding and modelling of how effects propagate to impacts on subsurface, facility and surface environments.</td>
</tr>
<tr>
<td>• Guidelines and regulations including standards and safety norms.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Mitigation of hydrogen reaction impacts</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>• Development of specific sensors, methods and monitoring strategies.</td>
</tr>
<tr>
<td>• Improvement of the matching and validation of models with subsurface observations.</td>
</tr>
<tr>
<td>• Determination of sensitivities and thresholds for observations for baselines and monitoring.</td>
</tr>
</tbody>
</table>
Subtask B

Presenter: SAM XIE, Curtin University

Lead Subtask-B

Hydrogen containment and integrity of porous rock storage

Integrity of salt cavern storage

Geophysical monitoring

Impacts on development and operations
Key Elements Associated with Storage Integrity in Salt Caverns and Depleted Gas Reservoirs
Cross-cutting nature of processes and impacts affecting storage integrity during UHS in subsurface

References
Intact shale caprock, which can seal to methane, would be able to seal to hydrogen through capillary pressure.

Hydrogen molecular diffusion and mechanical dispersion during cycling process will have a minor impact on hydrogen loss.

References
Hydrogen containment and integrity of porous rock storage

- Hydrogen has a minor impact on fluid – rock interactions.
- Cyclic loading also has a minor impact on reservoir rock integrity.

References
Kumar, et al., Scientific Reports, 2022 (https://doi.org/10.1038/s41598-022-25715-z)
Hassanpouryouzband et al., ACS Energy Lett. 2022, https://doi.org/10.1021/acsenergylett.2c01024

Schematic diagram of high-pressure, static batch reactor, and bottle test experimental setup.

Schematic illustration of the experimental setup including loading system, data acquisition.
Uncertainties in Storage Integrity – Porous rock storage

- Impact of geochemical reactions on rock strength and elastic properties
- Stress-enhanced dissolution-precipitation creep
- Stress corrosion cracking and subcritical crack growth
Integrity of salt cavern storage

- Salt caverns have been proven to maintain their mechanical integrity over the lifetime of at least several decades.
Impacts on development and operations

- **Leakage**
  - Intact shale caprocks which seal to methane, would be able to seal to hydrogen through capillary pressure.
  - The leakage mechanisms through fractures need to be investigated at different length and time scale during cycling process.

- **Induced seismicity**
  - Fault slip and fracture development/propagation. Failure mechanisms of hydrogen conditioned shale caprocks with pre-existing fractures for UHS needs to be investigated. This also applied to salt caverns with a certain mineral impurity.

- **Subsidence**
  - Pressure and temperature cycling could lead to reservoir fatigue.
  - Long term salt creep behaviour may lead to movement further away from the cavern wall.
Recommendations for geophysical monitoring

- Existing monitoring methods for hydrocarbons exploitation and storage and CO$_2$ storage remains relevant.

- 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.
Subtask C

STORAGE PERFORMANCE AND SCREENING

Presenter: Ed Hough, British Geological Survey

Lead Subtask-C

Hydrogen physics and thermodynamics relevant to storage in salt caverns

Hydrogen flow and recovery in porous rock and salt caverns

Cushion gas effects

Storage potential, screening criteria and ranking

Risks
Storage performance - scope

Storage demand profile

This determines the maximum production rate and duration (load and load duration). End use of hydrogen is also relevant.

Operational performance
- injection/production rates;
- working gas volume;
- cushion gas;
- quality of hydrogen required;
- load duration

Influenced by:
- Site specific geology;
- Engineering and construction
Hydrogen physics, thermodynamics, flow and recovery

Considerations:
- Physical and chemical properties of hydrogen differ from, e.g. Methane, CO₂
- Hydrogen may react in storage, or stimulate microbial populations
  - Quality of stored gas; reservoir performance; Loss of hydrogen
- Effect of repeated injection and withdrawal cycles and variations in storage pressures
- Physical properties can be altered due to hysteresis effects
- Changes in subsurface stress: Creep and loss of cavern volumes and storage capacities (caverns); Induced seismicity?
- Dissolution and diffusion, residual trapping

Relevant parameters:
- Geothermal gradient (1);
- Overburden pressure (2);
- Column height conversion factor (3);
- Compressibility factor (4);
- Mass of working gas (4);
- Energy storage capacity (4)
Cushion gas effects

Cushion gas demands can be **significant**

A larger storage complex may need a much greater amount of cushion gas - a significant **capital outlay**

**Alternative cushion gas compositions** are being considered:
- N₂, CH₄, CO₂

These could
- Reduce costs;
- Reduce carbon footprint;
- Reduce density contrast between hydrogen and formation waters;
- Increase costs? – reservoir management/post-storage processing and refining
Theoretical capacity estimates are...theoretical

Storage capacities and locations

Represent a maximum potential storage volume

Different studies apply different criteria

Geological Characterization, Screening and Ranking

Theoretical capacities give operators, decision-makers, planners a starting point

Progressive ranking and filtering: from theoretical capacities

No standard method

Some confidence from existing cavern storage schemes; less so for porous rock storage
Screening criteria

Cavern storage

- Required thickness and depth of halite
- Ratios of cavern height:diameter
- Over- and under-burden requirements
- Cavern shape (and correction factor)
- Cavern volume (and correction factor)
- Pillar thickness

Example: ranking (largest influence first):
- Halite lithology;
- Stage of exploration;
- Type of halite deposit;
- Halite volume;
- Depth of reservoir;
- Geothermal gradient

Porous rock storage

Hystories assessment:
Storage meets anticipated need

With an effective seal, and
- within viable depth ranges;
- Avoid leaking faults;
- suitable hydrogen trap;
- Subsurface and surface infrastructure

Also,
- Natural gas fields;
- Permeability and transmissivity values;
- Gas Initially in-place
- Avoid significant H₂S
- Production data

Key references:
Screening and ranking: (cavern) Lewandowska et al., 2018.
(Porous storage) Réveillère et al., 2022.
Storage volumes: (cavern) Caglayan et al., 2020;
Williams et al., 2022.
(Porous storage) Scafidi et al., 2020
Risks and links to other Subtask areas

**Technical Risks**
Mitigated by: Operational constraints/reservoir management; Cavern design; Scheme design; Geological characterisation; Measuring, monitoring and verification strategies

**Safety Risks**
Mitigated by: Geological characterisation; Design of infrastructure (e.g., casing, valves); Measuring, monitoring and verification strategies; Pre- and post-injection and withdrawal processing of H

**Economic Risks**
Mitigated by: Guidance and regulations; Operational constraints/reservoir management; Scheme design; Closure strategy
Subtask D

STORAGE FACILITIES & WELLS

Presenter: REMCO GROENENBERG,
TNO Netherlands Organization for Applied Scientific Research

Lead Subtask-D

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

Thursday 12th October 2023 – TCP-Task42- UHS External Stakeholder Webinar
The Key Components of an Underground H₂ Storage Facility

This subtask focuses on the technical design, engineering, operation and monitoring of top-side facilities and wells to ensure safe, reliable and affordable hydrogen storage.
What does/will a Storage Facility look like?

A facility for storage of hydrogen underground will largely look similar to one that stores natural gas.

Size, weight and costs of surface facilities scale primarily with the speed at which the hydrogen must be injected & withdrawn, not with the volumetric capacity of the storage.
Storage of Hydrogen vs. Natural Gas: What are the Differences?

Molecule size

Hydrogen is a smaller and lighter molecule than natural gas, has a higher diffusivity, and a lower viscosity.

Chemical reactivity

Hydrogen is highly reactive and other reservoir fluids can enhance negative interactions. It can also induce microbial activity, causing a.o. Microbially Induced Corrosion (MIC).

Cycling frequency (?)

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.

H₂ compatibility

New materials and components may be required that can withstand long-term operations under extended exposure to hydrogen or H₂S.

Differences in design of wells and facilities stem mostly from differences in characteristics and impact of hydrogen gas vs. natural gas.
Wells contain multiple barriers (primary and secondary) to prevent uncontrolled fluid flow (leakage) into the subsurface and through the wellbore towards the surface.

US salt cavern wells

EU salt cavern wells

EU gas field well

SMRI, 2023
What Areas of Well Designs are Particularly Affected?

- **Material selection** for all components of H₂ storage wells requires special attention:
  - **Metals** – embrittlement, corrosion and erosion.
  - **Elastomers** – loss of strength and elasticity, explosive decompression, changes on mass and volume.
  - **Cements** – changes in mechanical properties (strength, elasticity), porosity / permeability, influence on hardening process.

Well components:

- **Tubing / Casing**
  - Hydrogen diffusivity
  - Erosional velocity
  - Diameter

- **Connections**
  - Leak tightness
  - Durability
  - Type

- **Packers**
  - Leak tightness
  - Integrity

- **Wellhead**
  - Leak tightness
  - Durability

- **Emergency Shutdown Valve**
  - Leak tightness
  - Handling high flow velocities
**Process Flow Steps during Injection and Withdrawal**

**Before injection**, the hydrogen must be **compressed to above storage pressure, and cooled**

**After withdrawal** of the hydrogen from storage, it must be **dehydrated and purified to pipeline specs.**
How will Facility Design differ for UHS vs. UGS?

Applicable technology exists from experience with UGS (and industrial H₂ use), however there are some challenges for application (and/or re-use) for hydrogen storage:

- **Upscaling challenges** from current technology
- Challenges associated with **intermittent operations**
- **Onshore vs. offshore** facility locations

### Compressors

- State-of-art: **reciprocating compressors**
- **Not yet applied at scale** for UHS
- Only applied in continuous operation
- Turbo compressors (state-of-art in UGS) not designed for high % hydrogen streams
- Expect development to TRL 9 in the next 5-10 years (turbo)
- Compression challenges for unusual storage settings (e.g. **offshore**)
- Electric-powered preferred

### Gas treatment

- **Dehydration** (caverns) well understood
- State-of-art: TEG, glycol
- Large-scale H₂ **purification** challenging:
  - State-of-art PSA, TSA, membrane
  - Choice depends on gas composition vs. required purity level
  - High OPEX to have a high purity H₂ stream output with current technologies
  - How to handle the tail gas (waste) stream?

Thursday 12th October 2023 – TCP-Task42- UHS External Stakeholder Webinar
Recommendations for research, development and demonstration

- Functional requirements and designs for UHS - largely similar to UGS
- Verify and adapt individual component designs and materials to meet UHS needs
- Jointly develop and agree on safety and monitoring standards (operators, regulators)

**WELLS**
- Durability of materials and interfaces under long-term exposure to H₂ at varying P, T
- *Compatibility of materials for H₂-rich streams containing CO₂, H₂S with co-production of water*
- Impact of high partial H₂ pressures on microbial community dynamics and corrosion rates (MIC)
- Admissible H₂ flow velocities in wells to limit erosion & effectivity of sand exclusion mechanisms?
- *How desirable and feasible is it to re-use natural gas production (or storage) wells for H₂?*
- How to safely P&A legacy wells to minimize leakage risk?
- *Standards and regulations for hydrogen, e.g. admissible leakage rates and ways to test this.*

**FACILITIES**
- What frequency of starts and stops can be accommodated by compressors?
- How to optimally design the separation/purification units?
- *What to do with the waste stream (tail gas) after separation? Upgrade to NG-spec (=utilization)? Re-inject (=disposal)?*
- What are the limitations for compression and gas treatment in an offshore setting?
- Flow and quality metering
- PVT behavior
Presenter: ARNAUD REVEILLERE
Geostock

Lead Subtask-E

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
Subtask E – Main objectives: cost comparison and business cases

Cost is a cornerstone. It reflects the design, the safety requirements and performance objectives of underground storage techniques.

Business cases are deeply interrelated with cost and design objectives, and is impacted by withdrawn gas quality and the permitting issues.

Cost comparison of new underground hydrogen storages

H2 Conversion & Contamination

Storage Integrity

Storage Performance

Wells & Surface Facilities

Planning, Regulation, Safety and Society

Business cases Projections of demand and business cases

Thursday 12th October 2023 – TCP-Task42- UHS External Stakeholder Webinar
Detail on various CAPEX elements

- **Objective:** Typical and crucial requirement in most jurisdictions which provides the sole right to evaluate, drill and test prospects in a given area.
- **Relevance:** Essential for all storage types. Some licenses may be bound to existing production licenses (e.g., depleted gas fields, concessions for salt solution mining).
- **Challenges:** 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.
- **Cost impact:** 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.
## Comparison of public cost estimates

### Salt Caverns

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
<th>Hystorie s 2022</th>
<th>HyUndere r 2013</th>
<th>ENTEC 2022</th>
<th>Lord et al. 2014</th>
<th>DNV 2019</th>
<th>Ahluwalia et al. 2019</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Costs</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAPEX/energy</td>
<td>€/kWh</td>
<td>0.51</td>
<td>0.17</td>
<td>0.20</td>
<td>0.20</td>
<td>0.65</td>
<td>1.1</td>
</tr>
<tr>
<td>CAPEX/power</td>
<td>€/kW</td>
<td>205</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total CAPEX for the Basis of design</td>
<td>€/kgH₂</td>
<td>20</td>
<td>6</td>
<td>7</td>
<td>7</td>
<td>22</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>€/Nm³</td>
<td>1.8</td>
<td>0.5</td>
<td>0.6</td>
<td>0.6</td>
<td>2.0</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>€/kWh</td>
<td>0.6</td>
<td>0.17</td>
<td>0.20</td>
<td>0.20</td>
<td>0.65</td>
<td>1.1</td>
</tr>
<tr>
<td><strong>Basis of design (main)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cavern gas vol.</td>
<td>m³</td>
<td>8 x 380,000</td>
<td>500,000</td>
<td>no detail</td>
<td>580,000</td>
<td>no detail</td>
<td>80,000</td>
</tr>
<tr>
<td>LCCS depth</td>
<td>m</td>
<td>1,000</td>
<td>1,000</td>
<td></td>
<td>1,158</td>
<td>800</td>
<td></td>
</tr>
<tr>
<td>Hydrogen wvol.</td>
<td>tons H₂</td>
<td>8 x 2,635</td>
<td>4,000</td>
<td></td>
<td>1,912</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>Withdrawal to injection ratio</td>
<td></td>
<td>2.0</td>
<td>1.0</td>
<td></td>
<td>1.7</td>
<td>Assume d 1</td>
<td></td>
</tr>
<tr>
<td>Withdrawal cap.</td>
<td>ton H₂/day</td>
<td>8 x 23</td>
<td>259</td>
<td></td>
<td>118</td>
<td>50</td>
<td></td>
</tr>
</tbody>
</table>

### Aquifers & Depleted Gas Fields

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
<th>Hystorie s 2022</th>
<th>HyUnder 2013</th>
<th>Lord et al. 2014</th>
<th>DNV 2019</th>
<th>DNV 2019</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Costs</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAPEX/energy</td>
<td>€/kWh</td>
<td>0.20</td>
<td>0.03</td>
<td>0.42</td>
<td>0.25</td>
<td>0.11</td>
</tr>
<tr>
<td>CAPEX/power</td>
<td>€/kW</td>
<td>645</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total CAPEX for the Basis of design</td>
<td>€/kgH₂</td>
<td>20</td>
<td>1.0</td>
<td>14</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>€/Nm³</td>
<td>1.8</td>
<td>0.09</td>
<td>1.3</td>
<td>0.8</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>€/kWh</td>
<td>0.6</td>
<td>0.03</td>
<td>0.42</td>
<td>0.25</td>
<td>0.11</td>
</tr>
<tr>
<td><strong>Basis of design (main)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of wells</td>
<td>-</td>
<td>8 operatio n + 24 observati on</td>
<td>16 extra operatio n wells</td>
<td>1 operatio n well</td>
<td>no detail</td>
<td></td>
</tr>
<tr>
<td>Depth</td>
<td>m</td>
<td>1,200</td>
<td>1,500</td>
<td>1,400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen wvol.</td>
<td>tons H₂</td>
<td>46,000</td>
<td>312,800</td>
<td>1,912</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Withdrawal to injection ratio</td>
<td></td>
<td>2.0</td>
<td>1.7</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Withdrawal cap.</td>
<td>ton H₂/day</td>
<td>403</td>
<td>5,177</td>
<td>60</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**References**

3. "The role of renewable H₂ import & storage to scale up the EU deployment of renewable H₂," Energy Transition Expertise Centre, 2022.
These CAPEX comparison tables distinguish CAPEX/energy and CAPEX/power

Zuidswending
~320 MM Nm³

Géométhane
~300 MM Nm³

UHS is not a manufactured product

Costs are site-specific

Even in relatively comparable site conditions, costs depend on the storage capacity, and on the deliverability (injection/withdrawal flow rate) as well.
Boundary limits of these cost estimation - salt

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Exploration</td>
<td>no</td>
<td>yes («exploration»)</td>
<td>assumed not</td>
<td>no</td>
<td>assumed not</td>
<td>yes («geological survey»)</td>
</tr>
<tr>
<td>Leaching plant</td>
<td>yes</td>
<td>no</td>
<td>assumed not</td>
<td>yes</td>
<td>assumed not</td>
<td>assumed not</td>
</tr>
<tr>
<td>Cavern Construction (drilling, leaching, MIT, 1st fill)</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Cushion gas</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes («assumed»)</td>
</tr>
<tr>
<td>Above ground facilities (compression and drying)</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>assumed not</td>
<td>yes («assumed»)</td>
</tr>
<tr>
<td>Brine disposal</td>
<td>yes, pumps + 30 km pipeline</td>
<td>no</td>
<td>assumed not</td>
<td>assumed not</td>
<td>assumed not</td>
<td>10 miles pipeline + injection well</td>
</tr>
<tr>
<td>Engineering Management Services</td>
<td>yes</td>
<td>yes</td>
<td>assumed</td>
<td>assumed</td>
<td>assumed</td>
<td>assumed</td>
</tr>
<tr>
<td>Contingencies</td>
<td>yes</td>
<td>assumed</td>
<td>assumed</td>
<td>assumed</td>
<td>assumed</td>
<td>assumed</td>
</tr>
<tr>
<td>Owner costs</td>
<td>no</td>
<td>no</td>
<td>assumed not</td>
<td>no</td>
<td>assumed not</td>
<td>assumed not</td>
</tr>
</tbody>
</table>

A number of studies have proposed public CAPEX estimates for UHS

References


"The role of renewable H₂ import & storage to scale up the EU deployment of renewable H₂," Energy Transition Expertise Centre, 2022.


Boundary limits of these cost estimation – depleted fields and aq.

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

A number of studies have proposed public CAPEX estimates for UHS

References
O. Knuck, F. Crologno, R. Prelicz and T. Roopligh, “Assessment of the potential, the actors and relevant business cases for large scale and seasonal storage of renewable electricity by hydrogen underground storage in Europe,” HyUnder project report D3.1, 2013.
Comparison of public cost estimates – summary & conclusions

From the April 2023 TMR report:

- Project development costs are highly site-specific

- Further efforts are needed to identify and demonstrate gas treatment requirements and strategies for UHS in porous reservoir

- High variability is found in between public sources (this already had been identified)

- Limitations:
  - Limitation to public references
  - Limitation to CAPEX
Potential limitations and barriers for viable UHS business cases:

- **Purity requirement for $\text{H}_2$ grids**
  
  Gas quality specifications for hydrogen injection in transport pipelines may have an impact on the business cases because of costs associated with purification.

- **Immature market for $\text{H}_2$ storage**
  
  Uncertainty about the large-scale storage demand projection and expected areas of application.

- **Lack of experience in UHS operation**
  
  Experiences with pure UHS are limited to a few cases of salt cavern storage only.

- **Availability and knowledge of appropriate geological structures**
  
  The validation of site selection criteria is subject to further research and demonstration and the geological play for UHS is largely immature.

- **Geochemical and microbiological impacts**
  
  These effects may lead to higher costs and uncertainties with regards to the effective operation of storage and generation of revenues.

- **Cushion gas requirements**
  
  Assessing the opportunity of employing alternative gases as cushion gas.

- **Compatibility with existing infrastructure**
  
  UHS sites may reuse existing infrastructure elements (e.g., platforms, pipelines, wells).
As of today, there is no market that supports commercialization and upscaling of UHS. There are emerging insights in the key services and storage strategies that can be supplied by UHS. The valorization schemes are not yet in place, however.

The overall objective is finding the optimum storage and withdrawal capacity for different roles (max system benefits minus UHS costs)

Actions needed:
- 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.
Subtask F

SOCIETAL EMBEDDEDNESS OF UHS

Presenter: RICHARD SCHULTZ, Orion Geomechanics LLC

Lead Subtask-F

Towards technical and societal maturation and development

Implementation of societal embeddedness level for underground hydrogen storage

Progressing maturity of underground hydrogen storage projects
Technical maturation does not automatically imply that UHS is socially, legally or economically embedded. Non-technical (societal) aspects may prove to be a tougher hurdle to overcome than the technical aspects.

### Societal Embeddedness of UHS

#### Technical Readiness Levels

<table>
<thead>
<tr>
<th>Level</th>
<th>Stage</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mature</td>
<td>11</td>
<td>Proof of stability reached</td>
</tr>
<tr>
<td>Early adoption</td>
<td>10</td>
<td>Integration needed at scale</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>Commercial operation in relevant environment</td>
</tr>
<tr>
<td>Demonstration</td>
<td>8</td>
<td>First of a kind commercial</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>Pre-commercial demonstration</td>
</tr>
<tr>
<td>Large prototype</td>
<td>6</td>
<td>Full prototype at scale</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Large prototype</td>
</tr>
<tr>
<td>Small prototype</td>
<td>4</td>
<td>Early prototype</td>
</tr>
<tr>
<td>Concept</td>
<td>3</td>
<td>Concept needs validation</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Application formulated</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Initial idea</td>
</tr>
</tbody>
</table>

#### Societal Embeddedness Levels

<table>
<thead>
<tr>
<th>Level</th>
<th>Stage</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>5</td>
<td>Adapting to changing societal environment</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>Innovation embedded in societal environment</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>Societal aspects tested in system</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>Societal aspects assessed</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>Societal aspects explored</td>
</tr>
</tbody>
</table>
Societal Embeddedness of UHS

Societal Embeddedness includes 4 main dimensions which need to mature in parallel:

- Impact on the environment
- Policy & Regulatory framework
- Public and stakeholder involvement
- Market & (financial) resources

Source: Marit Sprenkeling, 2023

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Societal Embeddedness of UHS

- SEL-1 Exploration
  - Milestones, criteria, requirements
  - Milestones, criteria, requirements
  - Milestones, criteria, requirements
  - Milestones, criteria, requirements

- SEL-2 Development
  - Milestones, criteria, requirements
  - Milestones, criteria, requirements
  - Milestones, criteria, requirements
  - Milestones, criteria, requirements

- SEL-3 Demonstration
  - Milestones, criteria, requirements
  - Milestones, criteria, requirements
  - Milestones, criteria, requirements
  - Milestones, criteria, requirements

- SEL-4 Deployment
  - Milestones, criteria, requirements
  - Milestones, criteria, requirements
  - Milestones, criteria, requirements
  - Milestones, criteria, requirements

Governing impacts on environment
- Public and Stakeholder Involvement
- Policy and Regulations
- Market and resources

After: M. Sprenkeling T. Geerdink
## Societal Embeddedness of UHS – Example of requirements

<table>
<thead>
<tr>
<th>SEL Dimension</th>
<th>Examples of new societal aspects to be considered, relative to current UGS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impacts on Environment</td>
<td>A. 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), carbon footprint of UHS activities, safety aspects related to potential induced seismicity events, facility hazards, explosions, etc.</td>
</tr>
<tr>
<td></td>
<td>B. Strategies to deal with risks/negative impacts on the environment. Setting acceptable norms</td>
</tr>
<tr>
<td></td>
<td>C. Assessment of potential competition for space between UHS and other subsurface and surface activities and functions.</td>
</tr>
<tr>
<td></td>
<td>D. Identified cultural context and history, for example positive or negative experiences with similar storage technologies. This also interlinks with stakeholder involvement.</td>
</tr>
<tr>
<td></td>
<td>E. Possible advantages and positive impacts (e.g., economic, infrastructure, etc.).</td>
</tr>
</tbody>
</table>
**Societal Embeddedness of UHS – Example of scoring**

Provides a consistent approach for comparing UHS.

Displays progress across regions and cultures.

<table>
<thead>
<tr>
<th>TRL scale</th>
<th>Scoring TRL</th>
<th>SEL scale</th>
<th>Scoring SEL Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Mature TRL 11</td>
<td>SEL 5: Adapting to changing societal environment</td>
<td>Environmental impact</td>
</tr>
<tr>
<td>10</td>
<td>Early adoption TRL 9-10</td>
<td>SEL 4: Innovation proven in societal environment</td>
<td>Stakeholder involvement</td>
</tr>
<tr>
<td>9</td>
<td>Demonstration TRL 7-8</td>
<td>SEL 3: Social aspects included in system</td>
<td>Policy Regulation</td>
</tr>
<tr>
<td>8</td>
<td>Prototype TRL 4-6</td>
<td>SEL 2: Social aspects assessed</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Concept TRL 1-3</td>
<td>SEL 1: Social aspects explored</td>
<td></td>
</tr>
</tbody>
</table>

**UGS**
- UHS – Salt Caverns
- UHS – Depleted gasfields
- UHS - Aquifers

SEL scoring may differ per country/region.
Next steps – Recommendations towards a UHS Societal Embeddedness Framework

- More detailed exploration and definition of all relevant social aspects and associated requirements in each social dimension. This needs to be completed among others through stakeholder (expert and non-expert) interviews at local, national and international levels.

- Further develop and implement the SEL principles with interdisciplinary teams, to gain sufficient knowledge in all four social dimensions and to improve the representativeness and broader social support of results. Gather feedback in Stakeholder Workshop – January 2024

- 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.

- Exchange and publish learnings from projects/countries/regions to accelerate responsible worldwide UHS development and deployment.
Q&A DISCUSSION

Key challenges
De-risking technical and non-technical risks
Stakeholder needs
...

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Wrap-up and Outlook

Pathways to de-risking

- Bring together knowledge and information to increase the technological confidence in UHS.
- Assess and report methods and strategies for risk assessment and monitoring
- Investigate cost parameters and business model scenarios
- Assess and report the conditions for societal embeddedness of underground hydrogen storage
Wrap-up and Outlook

Outreach and knowledge sharing

- Final TCP-Task42 report expected end of 2024

- UHS Summer school:
  3rd edition confirmed as the 8-12th of July 2024 at the University of Edinburgh
  Intro classes, Main conference, Field trips, Demonstration projects, Geology
  Enjoy the Scottish traditions

- Contributions to Industry and Policy stakeholder events

- Follow our activities via Newsletters and social media (Linkedin Group)
Thank you for your participation and interest