Underground Hydrogen Storage

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Final version for ExCo review and Approval

Hydrogen TCP

Technology Collaboration Programme
by iea

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Annexes

Guidelines (taken from Hydrogen TCP's Handbook)

Please follow this structure and guidelines in order to present your Task's Work Plan. The detailed Task Work Plan expands on the description of the Task objectives, activities and results. It also specifies who is responsible for what, the required resources, the milestones, the task schedule and major products, and also includes an information plan.

A carefully prepared Work Plan is essential as it governs the operation of the Task. It should include resource requirements for the Task (experts, time, funds, facilities) and when the resources are required.

The Work Plan is drafted by the Task Manager and Subtask Leaders near the end of the Project Definition Phase. It is based on the collaborative activities and the national contributions that were agreed upon during the PDP.

The document should be revised and updated on a regular basis. This might be annually, but this will vary by Task. A brief 6-month work plan and status of milestones are included in the semi-annual status reports.

Background and Rationale

Future energy scenarios foresee a prominent and growing role for hydrogen as a clean and flexible energy carrier in multiple sectors of the energy system (e.g. electricity, industry, heating, transport). Intermittency and variability in energy production and consumption (e.g. wind/solar and heating) will require flexibility and balancing at hourly, daily and inter-seasonal timescales. It is very likely that a demand for large-scale hydrogen storage will emerge that exceeds the capacity of typical aboveground energy storage technologies.

The European HyUnder project, the results of which were published back in 2014, addressed the potential role that underground hydrogen storage (UHS) could play in providing flexibility in future energy systems with high percentages of variable renewables. However, the focus was primarily on the potential of salt caverns, while that of depleted hydrocarbon fields and aquifers was not evaluated in detail. In the meantime various studies have evaluated and emphasized the need for large-scale underground hydrogen storage in both salt caverns and porous reservoirs.

Subsurface reservoirs such as gas fields, aquifers and solution-mined salt caverns define proven and mature options for large-scale storage of natural gas and its components such as carbon dioxide and nitrogen. These gases are characterized by common natural occurrences (typically in mixed compositions) in the subsurface and have, in many instances, accumulated in porous and sealed reservoirs over geological time. Hydrogen however has different physical and chemical properties and its natural occurrences in the subsurface are rare.

Underground hydrogen storage is not yet ready for commercialization and upscaling. The different properties and behavior of hydrogen pose a range of research challenges which need to be resolved before the technology becomes mature enough. Underground storage concepts need to be tested and validated. The planning, upscaling and integration of UHS in the future energy system depends on geological screening of suitable reservoirs, evaluation of viable and safe subsurface and operational conditions, assessment of environmental and societal impacts and analysis of viable business models and concepts. These insights form the basis for establishing a robust regulatory framework and best practices for responsible and societally accepted development.

Task Description

Many steps need to be taken before safe and responsible large-scale deployment and commercialization of UHS becomes reality. Some countries are in the process of gaining approval for pilots, demonstration and commercial-scale storage sites yet these are lengthy processes. Timely preparation is key as lead times for development can be long (5-10 years) and the demand for large-scale, long-duration energy storage is expected to increase rapidly after 2030. This task therefore aims to advance the demonstration of UHS by bringing together research and industry activities from organizations across the world and by linking various related scientific, industrial and societal disciplines.

This Task focuses on research & innovation challenges to prove and demonstrate the technical, economic, and societal viability of underground hydrogen storage (UHS). This concerns storage options in porous reservoirs, salt caverns, and line-rock caverns. While salt caverns are already being deployed for static storage of hydrogen, there is a need to test the technical feasibility of fast-cyclic and high-performance injection and production as well as optimal management of dense clusters of them. The technical viability of hydrogen storage in porous reservoirs is relatively less developed, and as such, it is still under more fundamental scientific and technological investigations.

General Scope

In this task we consider all aspects that are needed to raise the technical readiness, demonstration, planning and commercialization of UHS. The following elements define the main scope:

- All subsurface formations, reservoirs and technologies that are considered as potentially viable options for UHS (e.g. salt caverns, depleted gas fields, saline aquifers, lined rock caverns), including characterization of reservoir and fluids
- Behavior and monitoring of hydrogen within subsurface reservoirs (e.g. geochemical, microbial, thermo-mechanical, hydrogeological effects, mixing/diffusion, etc.)
- UHS operations, concepts and techno-economic performance, cushion gas, purity/deblending
- Risks and risk management, including effects/hazards/impacts that could possible arise from UHS development (e.g. subsidence, seismicity, leakage).
- Surface facility components, wells designs, materials and safety aspects
- Business models, pathways towards commercialization and system integration of UHS
- Site screening, planning, decision support for the development of potential UHS sites
- Regulatory and legal aspects, standards
- Societal embedding of UHS, public acceptance and participation

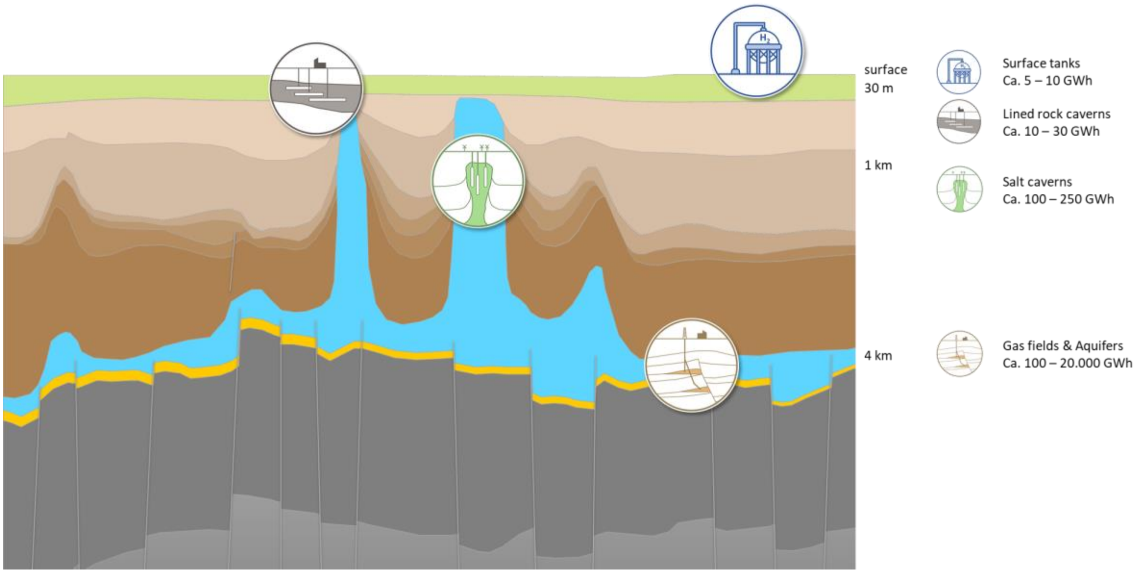

FIGURE 1: OVERVIEW OF MAIN SUBSURFACE OPTIONS FOR STORAGE

Objectives

The main objectives of this task are:

- To provide a comprehensive assessment of the technical (capacity, efficiency, safety, potential of infrastructure re-utilization) and economic feasibility for large-scale UHS development.
- To determine the potential for safe UHS development in the involved countries based on the results of technical and economic feasibility studies, including special limitations due to above-ground use of space and presenting the advantages and disadvantages of onshore and offshore hydrogen storage.
- To establish under which subsurface conditions hydrogen storage in porous reservoirs is technically feasible by conducting relevant laboratory experiments, field measurements and numerical modelling research that help make informed decisions based on a good understanding of the residual risks involved.
- To present business developers and policy makers with general guidelines and recommendations that enhance safe and economic UHS deployment in porous geological reservoirs, salt caverns and other man-made caverns.
- To prevent unnecessary duplication in research activities and seek opportunities for synergy and complementary activities that support acceleration of UHS while saving time and money

The task intends to support the acceleration of safe implementation of UHS through coordinated collaborations and knowledge dissemination. The ambition is to contribute to research within this area, be a technology monitor for ongoing and new activities as well as contributing to the development of a regulatory framework for hydrogen underground storage in the countries involved in the task.

Typically the task may result in following outcomes (to be defined by the participating experts and organizations):

- UHS technology benchmarks, capacity assessments and reviews
- Knowledge sharing events and workshops, networking events
- Reports and Proceedings from research and testing, research recommendations
- Guidelines, best practices and toolboxes for facilitating the evaluation, classification, licensing and safety assessment of UHS sites
- Scientific papers and publications promoting and advancing the technical economic, environmental and societally acceptable development of UHS
- Platform and tools for data and information exchange and standardization

Related topics

Hydrogen production, transport and use may be relevant for the feasibility, implementation and commercialization of UHS. Although these aspects are not considered part of the specific research scope, these topics may be part of the work and outputs from this task.

There is an overlap between the technical challenges and research scope of UHS, Underground Natural Gas Storage (UGS) and CO2 Storage (CC(U)S). The task stimulates research collaboration between these technologies provided that the resulting activities and results contribute to the objectives in this Task. In this context, the Task also seeks collaboration with other TCPs.

Structure

The task structure incorporates six subtasks (A-F) that are defined according to the main thematic research challenges that are currently in focus by industry, the scientific community and regulators. The scope of each subtask is explained in the following sections.

A. H2 conversion and contamination
B. Storage integrity
C. Storage performance
D. Surface facilities, wells and materials
E. Economics and system integration
F. Planning, regulation, safety and societal embedding

The activities in the subtasks will by supported by a variety of disciplines, competences and research facilities from participating organizations and experts. These include among others:

- Microbiology
- Geochemstry
- Geomechanics (rock / well bore)
- Hydrogeology
- Geological modelling, mapping and assessment
- Monitoring & verifications
- Reservoir modelling and simulation
- Risk management & assessment
- Geo-engineering
- Facility and well engineering
- Materials, components and equipment

- Energy systems modeling
- Economics, market and business concepts
- Legal and regulations
- Societal embedding & public acceptance

The task intends to address and support the progression of UHS through the different phases of technology readiness and development. To that end, the task results and reports will be structured according to the following main topics:

- Technical feasibility, uncertainties and proof of concepts
- Exploration and site screening
- Pilots and demonstration
- Upscaling and commercialization

The projects and competences presented by participating experts provide a firm basis and opportunity to initiate various activities under this task. Examples are:

- Technology reviews, research proceedings and recommendations
- Knowledge sharing, webinars, stakeholder events
- Link experimental research to field-scale pilots and demonstration projects
- Develop standards, tools and guidelines

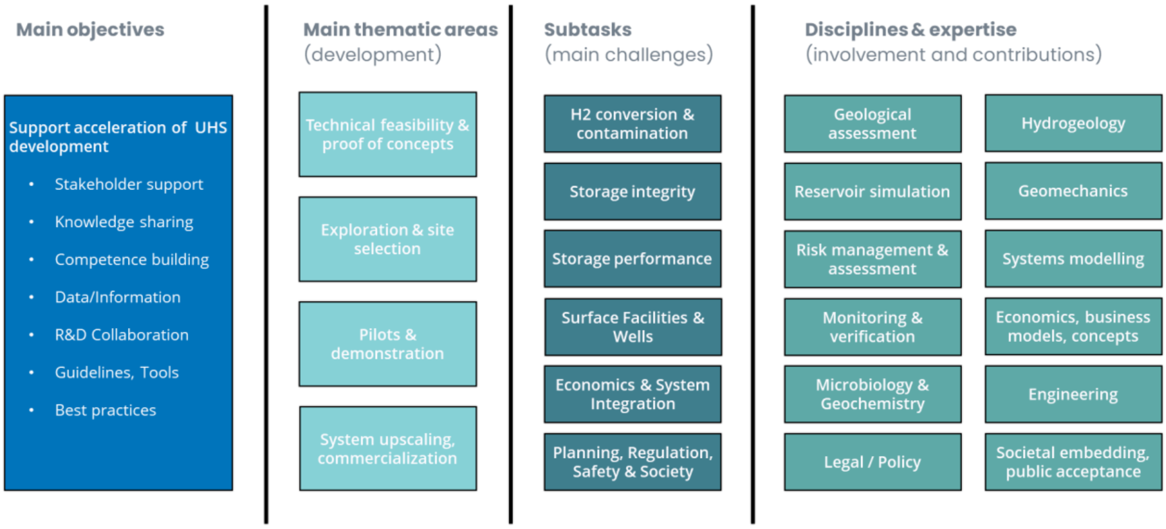

FIGURE 2: ENVISIONED TASK GOVERNANCE, STRUCTURE & OUTPUT

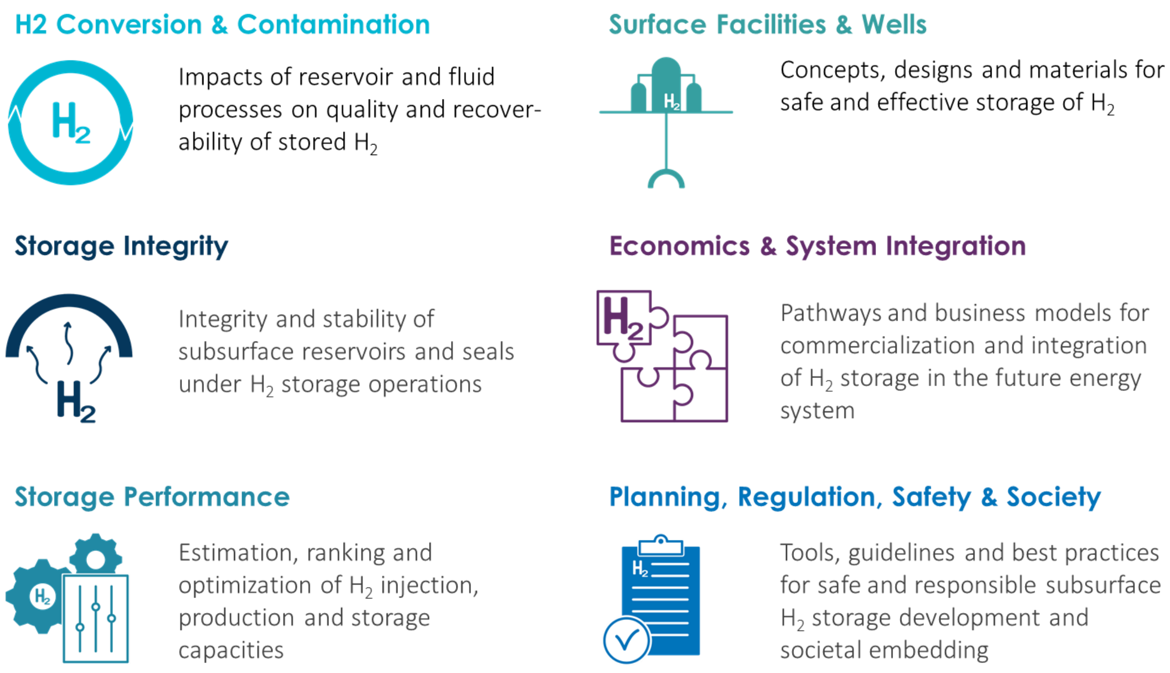

FIGURE 3: OVERVIEW OF SUBTASKS

The task and subtasks will be governed mainly by the main task coordinator, general task support and selected subtask leads who are grouped under the overarching subtask "Task Coordination". This subtask also governs communication, dissemination and exploitation.

Main Task Coordination:

- Task governance (together with Subtask Leads)
- Reporting to Hydrogen TCP ExCo and Secretariat
- Organize and support task meetings, workshops, events
- Final task report
- Communication and dissemination activities

Subtask A: H_2 conversion & contamination

One of the key aspects that distinguishes UHS from UGS is the way in which hydrogen reacts to the chemical composition of rock matrix, fluids and the presence of micro-organisms. This subtask focuses on microbial and geochemical processes which may lead to conversion of hydrogen and as a result impact the safety, efficiency, quality and recoverability in UHS.

Research scope:

- Laboratory experiments, modeling studies and in-situ pilots aiming to investigate effects and potential impacts in the reservoir resulting from:
  - Geochemical reactions with the rock matrix, formation water, other gases/fluids (e.g. cushion gas, remaining hydrocarbons, etc.) and well materials

    - Microbial processes
- Development of toolboxes, concepts and methods supporting the upscaling and implementation of experimental research results (laboratory-scale) to real environments (field scale):
    - Field screening and conditions for safe and efficient UHS
    - Supporting field development and operations
    - Monitoring and verification
    - Risk management, identification and quantification of uncertainties
- Standard operating procedures, guidelines and best practices for:
    - Sampling of field data
    - Experimental investigations, laboratory materials/equipment
    - Measuring and monitoring hydrogen in subsurface reservoirs
- Assess technology options such as underground methanation of hydrogen with CO_2, use of different types of cushion gases, etc.
- Benchmarking and mapping of potential UHS sites (based on geochemical and microbial criteria)

Key disciplines involved

- Microbiology
- Geochemistry
- Monitoring & verification
- Risk management & assessment
- Geological assessment

Subtask B: Storage integrity

The integrity and stability of storage reservoirs are crucial aspects for any underground storage project. Besides safety, these aspects may also determine the efficiency of the storage projects (e.g. recoverability) and the impacts on nearby subsurface activities and resources. This subtask specifically focuses on the subsurface processes and properties which determine the integrity and sealing capacity of the underground store (reservoir, caprock, faults) as well as the geomechanical behavior in response to (fast) cyclic injection and production of hydrogen.

Research Scope

- The gas tightness of different types of caprocks and well materials (like cements and casing materials) with regards to storage of hydrogen under high pressures (experimental, in-situ pilots/tests).
- Impact of hydrogen on caprock integrity, sealing capacity, reservoir stability and fault kinematics (experimental, in-situ).
- Cavern system integrity and stability. Influence of different cavern designs, formation characteristics and architecture of cavern clusters on (long-term) behavior of the salt (subsidence, creep, stability) and on the mutual effects of activities in neighboring caverns and other neighboring activities in the underground.

- Microbiological inhibition concepts
- Analysis of stress, strain, salt deformation and induced seismicity resulting from cyclic injection and production, including analysis of a cavern system with different dynamic loading cycles.
- Guidelines for safe storage development and operations and life-cycle management (including abandonment and after-care).
- Workflows, models and best-practices for geomechanical integrity assessment of reservoir, seal and wellhead.
- Workflows, models and best-practices for quantification of leakage rates and transport pathways
- Subsurface characterization (including salt heterogeneity) and monitoring techniques to detect hydrogen migration

Key disciplines involved:

- Geological assessment (reservoir, seal, overburden)
- Geomechanics (reservoir, seal and near-wellbore)
- Reservoir simulation (providing input/constraints)
- Hydrogeology (reactive transport modelling)
- Monitoring & verification
- Well engineering

Subtask C: Storage performance

This subtask focuses on aspects determining the performance of storage operations (site development) as well as the criteria and methods to rank and validate potential storage sites.

Research Scope

- Load profiles (flex. Services, cycling frequency, rates), injection/production scenario's
- Well performance, Reservoir (and cavern) capacity and performance
- Cushion gas requirements and options
- Recoverability (%H2 in withdrawal stream, contaminants)
- Evaluate storage development life cycle
- Improved prediction of the physics and thermodynamics of hydrogen behavior in the presence of different impurities.
- Imaging and monitoring (4D) of hydrogen flow through porous reservoir rocks and diffusion through salts. Experimental investigation and modelling of hydrogen flow behavior at the pore-scale under varying conditions and identifying the primary influencing parameters
- Investigate the efficiency of multiple cycles of hydrogen injection and withdrawal into porous rock and salt caverns
- Calculating the safe hydrogen storage pressures
- Mapping, characterizing and ranking potential sites based on performance/capacity/safety/environment criteria

- Developing optimization code to be coupled with reservoir simulators to be able to provide best scenarios of hydrogen storage and recovery. Modelling the roundtrip energy efficiency of hydrogen storage cycles and predicting the cost of energy based on this method. Validating models with field-scale pilots and incorporate all lessons learned in subtasks A and B.
- Analyze and assess interactions with existing (sub)surface usage and resources
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Key disciplines involved

- Engineering/dimensioning (cavern, reservoir, wells)
- Geomechanics, Geochemistry
- Well engineering
- Reservoir simulation, numerical modelling (for performance assessment)
- Monitoring & verification

Subtask D: Surface facilities & Wells

This subtask specifically focuses on the storage infrastructure elements including the engineering and design of the top-side facilities and the wells.

Research Scope

- Evaluate storage development life cycle (including abandonment and after-care).
- Well integrity and well engineering
- Well design and aboveground facilities design
- Workflows, models, best-practices for integrity assessment of wells
- Operational parameters (links to CO2-storage and UGS)
- Testing safety and monitoring concepts
- Best practices report: synthesis and review of operational end engineering aspects, compilation of pilot results
- Report on compatibility of materials for wells and surface facilities equipment for use with hydrogen, and guidelines for selection.
- Guidelines for re-use and decommissioning

Key disciplines involved

- Facility and well engineering
- Materials, components and equipment
- Risk management
- Wellbore geomechanics
- Reservoir simulation

Subtask E: Economics & System integration

This subtask aims to evaluate the (preferred) market conditions and criteria for commercialization and upscaling of UHS. Pilots and demonstration projects are gradually emerging in various countries. The absence of viable market conditions for large-scale hydrogen storage however, is a complicating factor for the definition of business cases.

Business cases should include the whole life-cycle of the storage activity (also including abandonment and after-care and the financial arrangement of the after-care).

Research Scope

- Investigation of the hydrogen value chain and the role of UHS therein
- Evaluation of factors and conditions which will determine the commercialization of UHS
- Evaluation of business model concepts and system integration
- UHS Project maturity classification schemes (e.g. UNFC)

Key disciplines involved

- Economics, business models, concepts
- Systems modelling

Subtask F: Planning, Regulation, Safety and Society

An important objective of this task is to support decision makers, regulators and other stakeholders with the safe and responsible large-scale deployment and commercialization of UHS.

Research Scope

- Standardization
- Best practices report: System, Economic, Regulatory and societal embedding of UHS in future energy systems
- Legal & regulatory frameworks for licensing, permitting and supervision
- Social site characterization and planning of stakeholder engagement.
- Guidelines for safe operation, risk management and monitoring
- Site portfolios and project classification for planning and decision support
- Societal embedding via public information, participation and education

Key disciplines involved

- Legal
- Policy
- Regulation
- Societal embedding & communication
- Stakeholder management

Participants

Confirmed /active participants

NOTE: This information will be updated after the Workplan has been approved and Participation Letters have been signed and submitted.

Interested parties

The following parties have shown and confirmed interest in joining the Task

Organization	Country
HYCHICO S.A.	AR
RAG Austria AG	AT
Woodside	AU
University of Adelaide	AU
Curtin University	AU
Dalian Institute of Chemical Physics | DICP	CN
Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences	DE
Ruhr-Universität Bochum	DE
DBI Gas- und Umwelttechnik GmbH	DE
STORAG Etzel	DE
Technical University of Freiburg	DE
Gas Storage Denmark	DK
Petroleum Oil & Gas (Naturgy Group)	ES
Fundación para el Desarrollo de las Nuevas Tecnologías del Hidrógeno en Aragón	ES
Centro Nacional del Hidrógeno (CNH2)	ES
REPSOL	ES
FCH-JU European Commission Fuel Cells and Hydrogen Joint Undertaking	EU
GeoStock	FR
ENI	IT
TNO	NL
Utrecht University	NL
EBN	NL

Gasunie / EnergyStock	NL
Shell	NL
Delft University of Technology	NL
Deltares	NL
Wageningen University & Research	NL
SodM (State Supervision of Mines)	NL
NORCE Norwegian Research Centre AS	NO
University of Bergen	NO
REN - Redes Energéticas Nacionais	PT
Risktec TUV	UK
University of Edinburgh	UK
Edinburgh Napier University	UK
Halliburton	UK/US/NL
University of Birmingham	UK
Gas Technology Institute	US

NOTES:

- Annex B provides further details including a summary of projects carried out by the interested participants, activities, expertise and interests which represent the type of involvement of parties in this task
- Parties will be mentioned as "Confirmed/active participants" after signing of the Participation Letter after the task workplan has been approved by the Hydrogen TCP Executive Committee

Potentially Interested Parties (awaiting confirmation)

The following parties have shown interest in joining the Task by participating in previous workshops or contacting the Task Manager. We are either still awaiting responses (confirmation of interest) from these partners, or meetings are to be planned.

Organization	Country
Storengy (meeting to be planned)	FR
University of Turin, Dep. of Earth Sciences (meeting to be planned)	IT
Nobian (follow-up meeting to be planned)	NL
Aramco (waiting for response)	SA
Centrica (meeting to be planned)	UK
RPS Energy (meeting to be planned)	UK
BP (meeting to be planned)	UK
Southern Company (waiting for response)	US
Abu Dhabi National Oil Company (waiting for response)	UAE

Associated organizations and networks

TCP
EOR TCP (Enhanced Oil Recovery)
GHG TCP (Green House Gas)
OG TCP (Oil and Gas)
ES TCP (Energy Storage)

Networks

The following partnerships, associations and networks are linked to UHS research. They represent members/organizations who may be involved in UHS projects and programmes or who have complementary expertise in this field. These entities will be engaged for collaboration or and joint MoU when the task starts.

Entity, network, partnership
Hydrogen Europe Partnership
Clean Energy Technology Partnership
CO2GeoNet

EASE
EuroGeoSurveys
ENeRG
UNECE

General Task Events and Timeline

Task Implementation Kick-Off

The Task Manager organize an Task Kick-Off Meeting and workshop in Q1/Q2 of 2022. The main objectives of this Kick-Off are to

- Detail and start defined activities under the Task and Subtasks
- Confirm expected contributions and roles of each participant
- Discuss and confirm the Task Communication and Dissemination Plan

The outcomes of Task Kick-Off (detailed activity plans, communication plan, etc.) will be reported by the Task Manager and Subtask Leads in a Task Kick-Off Report and an update of the Task workplan.

Task meetings

The Task Manager will initiate semi-annual Task Meetings during the period that the task is in force (2022-2024). These meetings will either be organized as live events or be held in the form of online meetings/workshops. This will be decided on the basis of the actual situation (e.g. COVID-19) and the opportunities to host meetings. The intention is to have at least one live event where the participants can meet in person. In the case of live-events, the Task Manager will engage task participants for possibilities to host a meeting. If possible and appropriate, live task meetings will be organized in conjunction with other relevant UHS-related events (e.g. conferences, seminars).

All participants are expected to attend the task meetings and to report/present proceedings of relevant UHS research activities and events. The following general agenda is proposed:

- Presentation and Review of Task proceedings, events and current activities
- Technical presentations (specific projects and research work by participants)
- Evaluation of new research opportunities, initiate new activities and events
- Discuss potential new Participants who may be invited to the task

From the meeting outcomes, the Task Manager and Subtask Leads will provide a semi-annual report to the Hydrogen TCP ExCo on the progress and results of the work performed under the Task Programme.

The second Task Meeting in each year will be planned in Q3/Q4 and results in an updated Task Workplan which will be presented to the Hydrogen TCP ExCo for approval.

Final Task Conference

Within 6 months after the conclusion of the Task activities, the Task Manager and Subtask Leads will produce a final Task Report which synthesizes all the results of research activities carried out under the Task. This report will be presented during a Final Task Conference for IEA representatives and relevant stakeholders.

Timeline of planned task meetings and general events and activities.

Milestone / Action / Event	Date	Document/deliverable
ExCo Review & Approval of Task Workplan	December 2021	Workplan / Task Annex
Confirmation of task participants	January/February 2022	Participants Letter
Task Implementation Kick Off	March/April 2022	Task Kick-off report and detailed activity plan
1st Task (Autumn) meeting and Technology Review workshop	October/November 2022	Task briefing 1st Technology Review and proceedings
ExCo approval workplan update	December 2022	Updated workplan
2nd Task (Spring) meeting	April/May 2023	Task briefing
3rd Task (Autumn) meeting and Technology Review workshop	October/November 2023	Task briefing 2nd Technology Review and proceedings
ExCo approval workplan update	December 2023	Updated workplan
4th Task (Spring) meeting	April/May 2024	Task briefing
Final Task meeting	October/November 2024	Task briefing Final Technology Review and proceedings Setup of final Task Report
Final Task Stakeholder Conference	March/April/May 2025	Final Task Report Conference proceedings