HyUSPRe

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

Final HyUSPRe dissemination event - Utrecht

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The HyUSPRe consortium

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Co-funded by the European Union

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Executive summary

The HyUSPRe consortium met in Utrecht, the Netherlands, on 19 June 2024 for its final conference. The conference had 50 face-to-face participants and another 25 attendees followed the lectures online. Consortium members shared their research results to a wider public after and of course this conference was also a farewell moment after having carried out a challenging research program for almost three years.

The program included a series of lectures, a poster session and was concluded with a BBQ in the Botanical Gardens. All presentations, lectures and posters, are attached to this report.

About HyUSPRe

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

The HyUSPRe project researches the feasibility and potential of implementing large-scale storage of renewable hydrogen in porous reservoirs in Europe. This includes the identification of suitable geological reservoirs for hydrogen storage in Europe and an assessment of the feasibility of implementing large-scale storage in these reservoirs technologically and economically towards 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 towards 2050; indicating the role of large-scale hydrogen storage in achieving a zero-emissions energy system in EU by 2050.

This project has two specific objectives. Objective 1 concerns the assessment of the technical feasibility, risks, and potential of large-scale underground hydrogen storage in porous reservoirs in 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, establish more accurate cost estimates and identify the potential business case for hydrogen storage in porous reservoirs. Suitable stores 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 hydrogen stores 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 the basis to develop future scenario roadmaps and prepare for demonstrations.

Document information, revision history, approval status

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Version	Name	Delivery date	Summary of changes
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V02	R. Groenenberg	2024.06.24	Commented version
V03	H. Cremer	2024.06.26	Final corrected and edited version

Approval status

Role	Name	Delivery date
Deliverable responsible:	TNO	
Task leader:		
WP leader:	H. Cremer	2024.06.24
HyUSPRe lead scientist	R. Groenenberg	2024.06.24
HyUSPRe consortium manager:	H. Cremer	2024.06.27

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1 Final conference program

The HyUSPRe consortium and professionals from the hydrogen industry met in Utrecht, the Netherlands, on 19 June, 2024 for the project's one-day final conference. A total of 50 colleagues were present physically in Utrecht whereas another 25 colleagues followed the program online.

The program started with a key note about HyUSPRe's vision and roadmap for the implementation of hydrogen storage in Europe until 2050. In the following two sessions, the main results of HyUSPRe were shared with the audience in various topical talks and a total of 17 posters. The session included also a presentation about HyUSPRe's sister project Hystories and Uniper's pilot storage project HyStorage.

HyUSPRe

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

Detailed Conference Program

08.15 – 08.45 Registration
08.45 – 09.00 Welcome (*Holger Cremer*, TNO, HyUSPRe coordinator
Welcome (*Serge van Gessel*, TNO, IEA TCP Task 42 coordinator)

09.00 – 12.00 (face-to-face and virtual)
09.00 – 10.00 2050 hydrogen storage landscape in Europe: vision and roadmap (*Remco Groenenberg*, TNO)

10.00 – 10.30 Break

Hydrogen storage assessments and implemenation scenarios
10.30 – 11.00 What the HyUSPRe hydrogen storage story maps tell us (*Andrew Cavanagh*, University of Edinburgh)
11.00 – 11.30 Techno-economic assessment of EU scale hydrogen system scenarios (*Theresa Groß*, Forschungszentrum Jülich)
11.30 – 12.00 What did we learn from the 'sister' project Hystories (*Arnaud Réveillère*, Geostock)

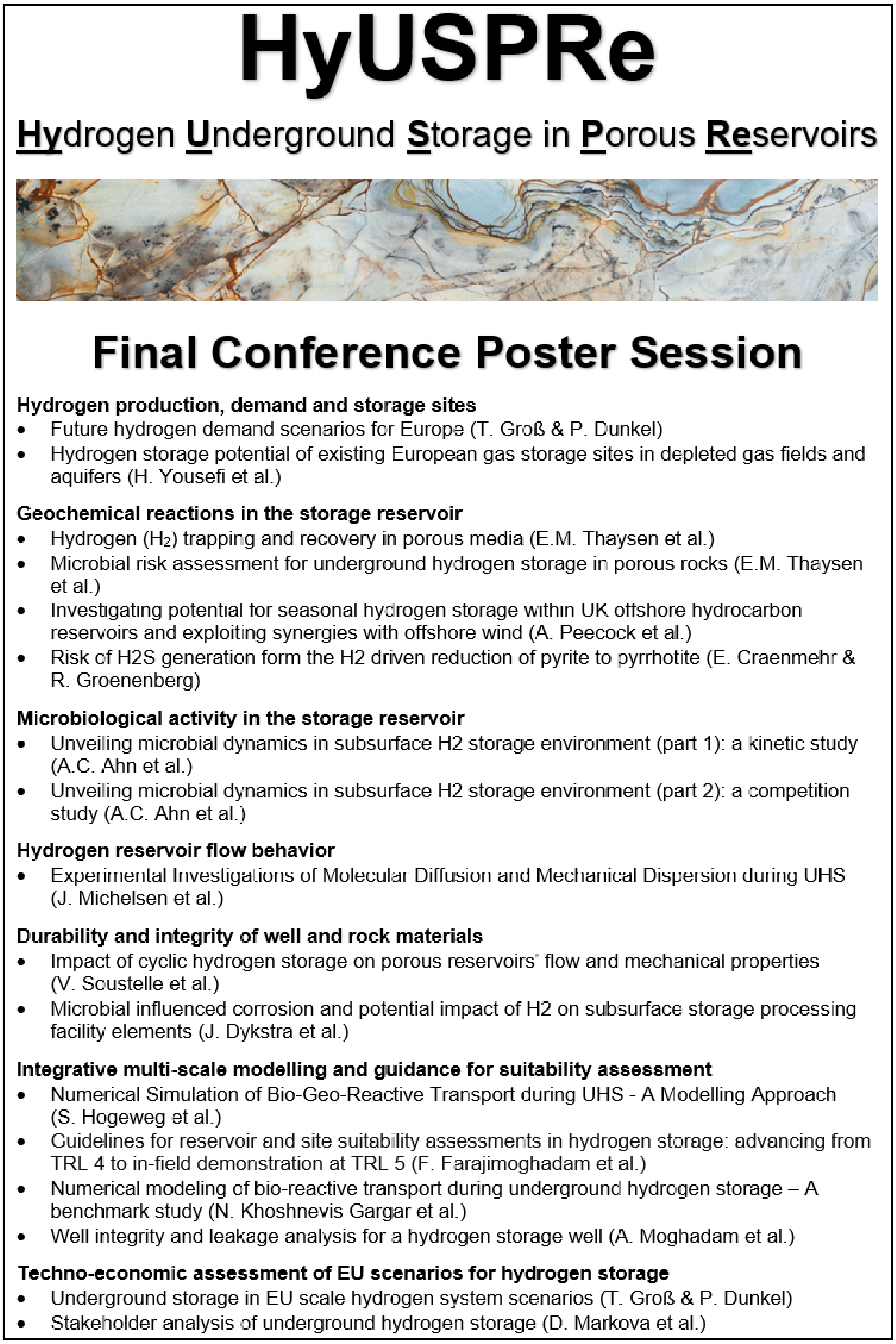
12.00 – 13.00 Lunch break

13.00 – 15.00 (face-to-face and virtual)
Impact of cyclic hydrogen storage on the reservoir and well system
13.00 – 13.30 Durability and integrity of rock and well materials under hydrogen storage conditions (*Jan ter Heege*, TNO)
13.30 – 14.00 Geochemical reactions induced by hydrogen in the reservoir (*Katriona Edlmann*, University of Edinburgh)
14.00 – 14.30 Microbiological activity in the reservoir under hydrogen storage conditions (*Diana Sousa*, Wageningen University)
14.30 – 15.00 A real world example: the HyStorage pilot project, Germany (*Gion Strobel*, Uniper)

15.00 – 17.00 (face-to-face only)
15.00 – 17.00 Poster session showing HyUSPRe results

17.30 – 21.00
17.30 – 21.00 BBQ in the Botanical Gardens

The scientific part of the final conference was concluded with a poster session where detailed results of the technical HyUSPRe work packages were introduced to the audience. Displayed posters are listed below and all posters are shown in the appendix.



HyUSPRe

Hydrogen Underground Storage in Porous Reservoirs

Final Conference Poster Session

Hydrogen production, demand and storage sites

- Future hydrogen demand scenarios for Europe (T. Groß & P. Dunkel)
- Hydrogen storage potential of existing European gas storage sites in depleted gas fields and aquifers (H. Yousefi et al.)

Geochemical reactions in the storage reservoir

- Hydrogen (H_2) trapping and recovery in porous media (E.M. Thaysen et al.)
- Microbial risk assessment for underground hydrogen storage in porous rocks (E.M. Thaysen et al.)
- Investigating potential for seasonal hydrogen storage within UK offshore hydrocarbon reservoirs and exploiting synergies with offshore wind (A. Peecock et al.)
- Risk of H2S generation form the H2 driven reduction of pyrite to pyrrhotite (E. Craenmehr & R. Groenenberg)

Microbiological activity in the storage reservoir

- Unveiling microbial dynamics in subsurface H2 storage environment (part 1): a kinetic study (A.C. Ahn et al.)
- Unveiling microbial dynamics in subsurface H2 storage environment (part 2): a competition study (A.C. Ahn et al.)

Hydrogen reservoir flow behavior

- Experimental Investigations of Molecular Diffusion and Mechanical Dispersion during UHS (J. Michelsen et al.)

Durability and integrity of well and rock materials

- Impact of cyclic hydrogen storage on porous reservoirs' flow and mechanical properties (V. Soustelle et al.)
- Microbial influenced corrosion and potential impact of H2 on subsurface storage processing facility elements (J. Dykstra et al.)

Integrative multi-scale modelling and guidance for suitability assessment

- Numerical Simulation of Bio-Geo-Reactive Transport during UHS - A Modelling Approach (S. Hogeweg et al.)
- Guidelines for reservoir and site suitability assessments in hydrogen storage: advancing from TRL 4 to in-field demonstration at TRL 5 (F. Farajimoghadam et al.)
- Numerical modeling of bio-reactive transport during underground hydrogen storage – A benchmark study (N. Khoshnevis Gargar et al.)
- Well integrity and leakage analysis for a hydrogen storage well (A. Moghadam et al.)

Techno-economic assessment of EU scenarios for hydrogen storage

- Underground storage in EU scale hydrogen system scenarios (T. Groß & P. Dunkel)
- Stakeholder analysis of underground hydrogen storage (D. Markova et al.)

2 Event report

The final conference took place at the premises of the Geological Survey of the Netherlands, a division of the Energy and Materials Transition unit of TNO (Netherlands Organization for Applied Scientific Research) in Utrecht. 50 colleagues followed the invitation and attended the conference face-to-face. Another 25 colleagues followed the program online – the oral presentations were streamed.

The organizers had built an interesting program covering all topics studied by the HyUSPRe consortium during the last three years. The morning session focused on the potential of hydrogen underground storage (UHS) in Europe now and in the coming decennia and emphasized the actions that are required to make UHS a significant contributor to Europe's energy transition. The afternoon session gave overall summaries of the experimental program that has been performed in HyUSPRe.

At the HyUPSRe final conference in Utrecht, 19 June 2024.

After the welcome words given by HyUSPRe's coordinator and the IEA TCP Task 42 coordinator, the program started with a presentation about the vision on UHS and roadmap for UHS implementation until 2050 that was developed by the HyUSPRe team. The roadmap, digitally available here, suggest a catalogue of actions that should be implemented for a successful roll-out of UHS in the coming decennia.
Following this kick-off talk, more detailed presentations shed light on the potential of UHS in Europe (see UHS potential StoryMap) and on the techno-economic assessment of hydrogen system scenarios for Europe (see study report here). The morning session was concluded with a contribution about the Hystories (**Hy**drogen **stor**age **i**n **E**uropean **s**ubsurface) project which was the sister project of HyUSPRe that finished in June 2023.

After the lunch break, the afternoon session offered three presentations on results of HyUSPRe's experimental program that intensively studied geochemical, geomechanical and microbial implications of UHS. Interested readers are recommended to visit the HyUSPRe website for download of various research reports. All three talks saw a lively discussion showing that reaction patterns of hydrogen in underground porous reservoirs are not yet fully understood. The afternoon session was concluded with the learnings so far made in the real-life storage project HyStorage, a pilot project of Uniper in Germany.

The technical part of the final conference was concluded with a two-hour poster session where many of HyUSPRe's achieved results were discussed in more detail. The displayed posters provided a good overall summary of the research done in the seven technical work packages (see headers in the overview in subchapter 1.2). All posters are shown in Chapter 3; for inquiries readers should send an e-mail to the contact given on the posters.

After a long but inspiring day full of lectures and posters, the participants enjoyed a delicious BBQ in the Botanical Gardens.

All technical presentations and posters are added to this report in chapter 3: Presentations.

3 Presentations

3.1 Oral presentations

Welcome notes

[01] Welcome *Holger Cremer*, TNO, HyUSPRe coordinator
[02] Welcome (*Serge van Gessel*, TNO, IEA TCP Task 42 coordinator)

Key note

[03] 2050 hydrogen storage landscape in Europe: vision and roadmap (*Remco Groenenberg*, TNO)

Hydrogen storage assessments and implemenation scenarios

[04] What the HyUSPRe hydrogen storage story maps tell us (*Andrew Cavanagh*, University of Edinburgh)
[05] Techno-economic assessment of EU scale hydrogen system scenarios (*Theresa Groß*, Forschungszentrum Jülich)
[06] What did we learn from the ‘sister’ project Hystories (*Arnaud Réveillère*, Geostock)

Impact of cyclic hydrogen storage on the reservoir and well system

[07] Durability and integrity of rock and well materials under hydrogen storage conditions (Jan ter Heege, TNO)
[08] Geochemical reactions induced by hydrogen in the reservoir (Katriona Edlmann, University of Edinburgh)
[09] Microbiological activity in the reservoir under hydrogen storage conditions (Diana Sousa, Wageningen University)
[10] A real world example: the HyStorage pilot project, Germany (Gion Strobel, Uniper)

[01] Welcome *Holger Cremer*, TNO, HyUSPRe coordinator

[02] Welcome (*Serge van Gessel*, TNO, IEA TCP Task 42 coordinator)

HyUSPRe

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

Welcome at the Final Conference

Hydrogen
Underground
Storage in
Porous Reservoirs
HyUSPRe

Clean Hydrogen Partnership

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Hydrogen Underground Storage in Porous Reservoirs

Welcome Serge van Gessel

Task 42 coordinator of IEA's Hydrogen Technology Collaboration Program

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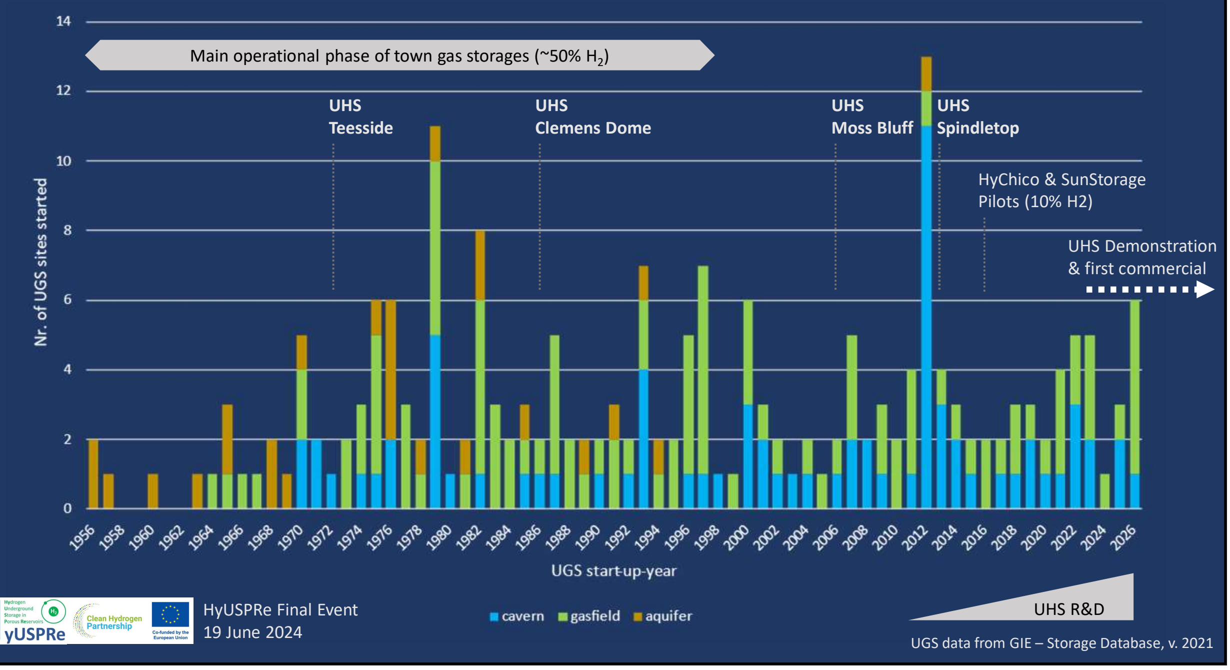
A brief history of Underground Gas Storage in Europe



HyUSPRe Final Event
19 June 2024

UGS data from GIE – Storage Database, v. 2021

Key note

[03] 2050 hydrogen storage landscape in Europe: vision and roadmap (*Remco Groenenberg*, TNO)

2050 UNDERGROUND HYDROGEN STORAGE (UHS) LANDSCAPE IN EUROPE: VISION AND ROADMAP

Remco Groenenberg, lead scientist of the HyUSPRe project
On behalf of the HyUSPRe consortium
HyUSPRe final event, June 19, 2024

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.

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This roadmap constitutes a collective view of the HyUSPRe consortium. The consortium partners endorse the general thrust of the arguments made in this roadmap but should not be taken as agreeing with every single finding or recommendation. The consortium partners have not been asked to formally endorse the report

1

HyUSPRe consortium

INDUSTRY

- **CENTRICA – United Kingdom**
- **EBN – Netherlands**
- **EQUINOR – Norway**
- **Hungarian Gas Storage - Hungary**
- **NAFTA – Slovakia**
- **NEPTUNE – Netherlands**
- **RAG – Austria**
- **Shell – Netherlands**
- **SNAM – Italy**
- **UNIPER – Germany**

RESEARCH INSTITUTES

- **TNO – NL (project coordinator)**
- **Energy Institute Linz – Austria**
- **Fondazione Bruno Kessler – Italy**
- **FZ Jülich – Germany**

UNIVERSITIES

- **University of Edinburgh – UK**
- **Clausthal University – Germany**
- **Wageningen University – Netherlands**

FUNDING ORGANISATIONS

- **Clean Hydrogen Partnership**
- **European Union**

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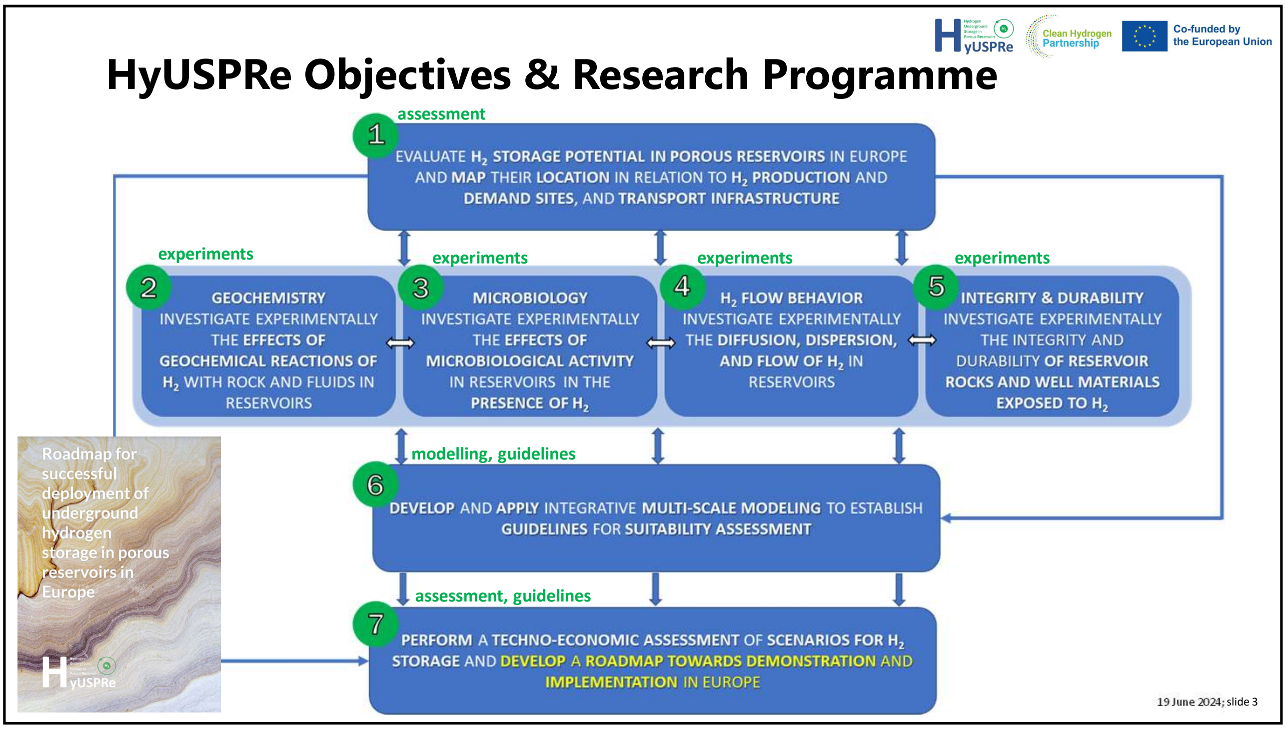


HyUSPRe Objectives & Research Programme

assessment

1 EVALUATE H_2 **STORAGE POTENTIAL IN POROUS RESERVOIRS** IN EUROPE AND **MAP** THEIR **LOCATION** IN RELATION TO H_2 **PRODUCTION** AND **DEMAND SITES**, AND **TRANSPORT INFRASTRUCTURE**

experiments

2 **GEOCHEMISTRY** INVESTIGATE EXPERIMENTALLY THE **EFFECTS OF GEOCHEMICAL REACTIONS OF** H_2 WITH ROCK AND FLUIDS IN RESERVOIRS

experiments

3 **MICROBIOLOGY** INVESTIGATE EXPERIMENTALLY THE **EFFECTS OF MICROBIOLOGICAL ACTIVITY** IN RESERVOIRS IN THE **PRESENCE OF** H_2

experiments

4 H_2 **FLOW BEHAVIOR** INVESTIGATE EXPERIMENTALLY THE **DIFFUSION, DISPERSION, AND FLOW OF** H_2 IN RESERVOIRS

experiments

5 **INTEGRITY & DURABILITY** INVESTIGATE EXPERIMENTALLY THE INTEGRITY AND DURABILITY OF **RESERVOIR ROCKS AND WELL MATERIALS EXPOSED TO** H_2

modelling, guidelines

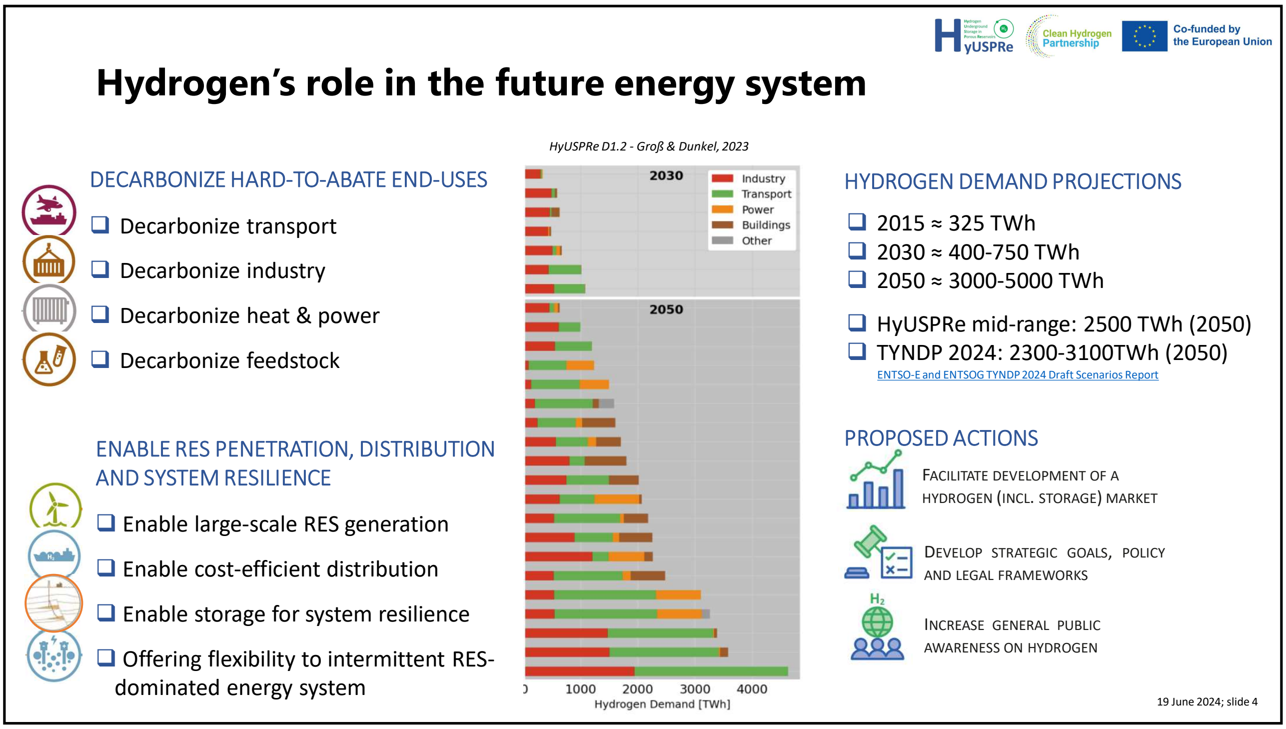
6 **DEVELOP** AND **APPLY** INTEGRATIVE **MULTI-SCALE MODELING** TO ESTABLISH **GUIDELINES** FOR **SUITABILITY ASSESSMENT**

assessment, guidelines

7 **PERFORM** A **TECHNO-ECONOMIC ASSESSMENT** OF **SCENARIOS** FOR H_2 **STORAGE** AND **DEVELOP A ROADMAP TOWARDS DEMONSTRATION** AND **IMPLEMENTATION** IN EUROPE

Roadmap for successful deployment of underground hydrogen storage in porous reservoirs in Europe

19 June 2024; slide 3



Hydrogen's role in the future energy system

DECARBONIZE HARD-TO-ABATE END-USES

- ❑ Decarbonize transport
- ❑ Decarbonize industry
- ❑ Decarbonize heat & power
- ❑ Decarbonize feedstock

ENABLE RES PENETRATION, DISTRIBUTION AND SYSTEM RESILIENCE

- ❑ Enable large-scale RES generation
- ❑ Enable cost-efficient distribution
- ❑ Enable storage for system resilience
- ❑ Offering flexibility to intermittent RES-dominated energy system

HyUSPRe D1.2 - Groß & Dunkel, 2023

HYDROGEN DEMAND PROJECTIONS

- ❑ 2015 ≈ 325 TWh
- ❑ 2030 ≈ 400-750 TWh
- ❑ 2050 ≈ 3000-5000 TWh

- ❑ HyUSPRe mid-range: 2500 TWh (2050)
- ❑ TYNDP 2024: 2300-3100TWh (2050)

ENTSO-E and ENTSOG TYNDP 2024 Draft Scenarios Report

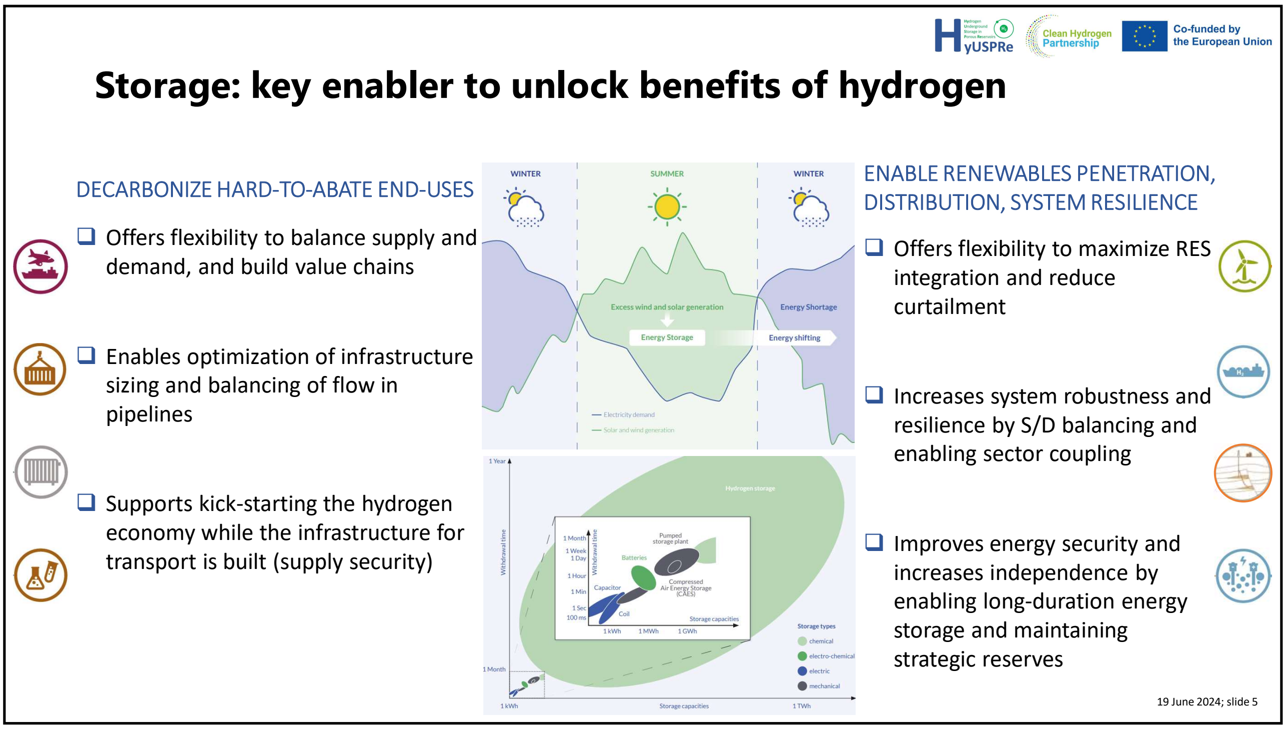
PROPOSED ACTIONS

FACILITATE DEVELOPMENT OF A HYDROGEN (INCL. STORAGE) MARKET

DEVELOP STRATEGIC GOALS, POLICY AND LEGAL FRAMEWORKS

INCREASE GENERAL PUBLIC AWARENESS ON HYDROGEN

19 June 2024; slide 4



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Storage: key enabler to unlock benefits of hydrogen

DECARBONIZE HARD-TO-ABATE END-USES

- ☐ Offers flexibility to balance supply and demand, and build value chains
- ☐ Enables optimization of infrastructure sizing and balancing of flow in pipelines
- ☐ Supports kick-starting the hydrogen economy while the infrastructure for transport is built (supply security)

ENABLE RENEWABLES PENETRATION, DISTRIBUTION, SYSTEM RESILIENCE

- ☐ Offers flexibility to maximize RES integration and reduce curtailment
- ☐ Increases system robustness and resilience by S/D balancing and enabling sector coupling
- ☐ Improves energy security and increases independence by enabling long-duration energy storage and maintaining strategic reserves

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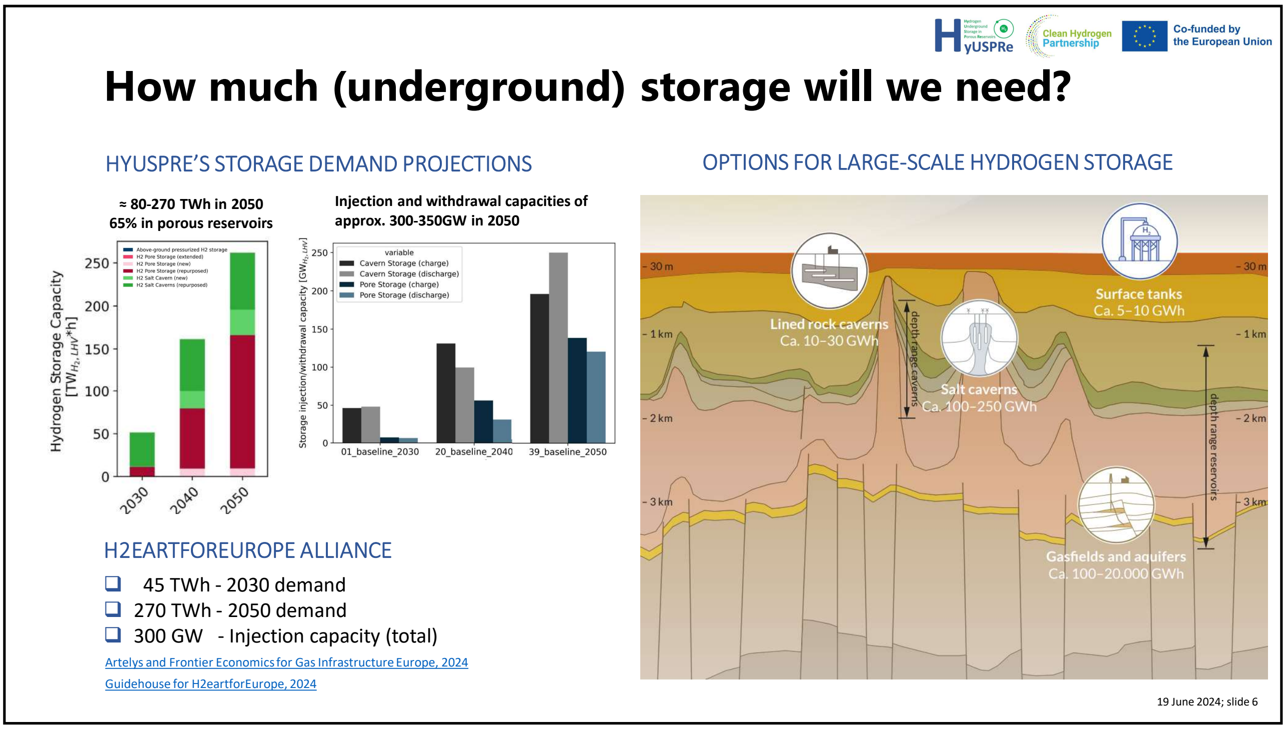

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How much (underground) storage will we need?

HYUSPRE'S STORAGE DEMAND PROJECTIONS

≈ 80-270 TWh in 2050
65% in porous reservoirs

Injection and withdrawal capacities of approx. 300-350GW in 2050

OPTIONS FOR LARGE-SCALE HYDROGEN STORAGE

H2EARTFOREUROPE ALLIANCE

- ☐ 45 TWh - 2030 demand
- ☐ 270 TWh - 2050 demand
- ☐ 300 GW - Injection capacity (total)

Artelys and Frontier Economics for Gas Infrastructure Europe, 2024

Guidehouse for H2eartforEurope, 2024

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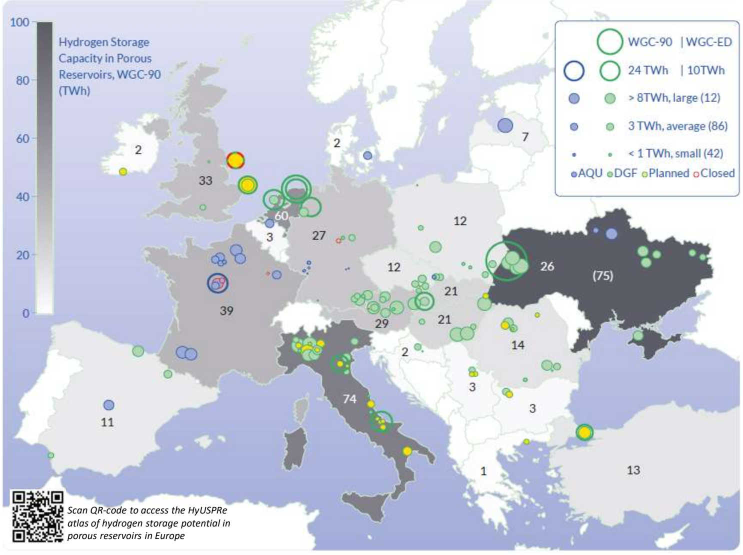
Storage potential in porous reservoirs in Europe

POROUS RESERVOIRS (GASFIELDS AND AQUIFERS) CURRENTLY OPERATIONAL (OR PLANNED) FOR NATURAL GAS STORAGE



Scan QR-code to access the HyUSPRe atlas of hydrogen storage potential in porous reservoirs in Europe

H_2 Storage Capacity TWh

Ukraine*	26		
Hungary	21	Netherland	60
Romania	14	United Kingdom	33
Poland	12	Germany	27
Latvia	7	Belgium	3
Bulgaria	3	Denmark	2
Serbia	3	Ireland	2
Eastern	86	Northwestern	127
Italy	74		
France	39	Austria	29
Turkey	13	Slovakia	21
Spain	11	Czechia	12
Greece	1	Croatia	2
Southern	138	Central	64
Total	**415**		

Hydrogen Underground Storage in Porous Reservoirs
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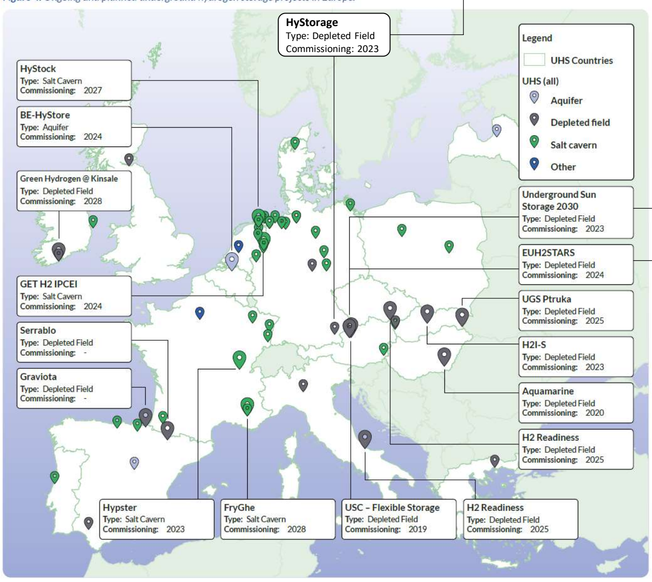
Current status of UHS in porous reservoirs

Figure 4: Ongoing and planned underground hydrogen storage projects in Europe.



HyStorage
Type: Depleted Field
Commissioning: 2023

HyStock
Type: Salt Cavern
Commissioning: 2027

BE-HyStore
Type: Aquifer
Commissioning: 2024

Green Hydrogen @ Kinsale
Type: Depleted Field
Commissioning: 2028

GET H2 IPCEI
Type: Salt Cavern
Commissioning: 2024

Serrablo
Type: Depleted Field
Commissioning: -

Graviota
Type: Depleted Field
Commissioning: -

Hypster
Type: Salt Cavern
Commissioning: 2023

FryGhe
Type: Salt Cavern
Commissioning: 2028

USC – Flexible Storage
Type: Depleted Field
Commissioning: 2019

H2 Readiness
Type: Depleted Field
Commissioning: 2025

Underground Sun Storage 2030
Type: Depleted Field
Commissioning: 2023

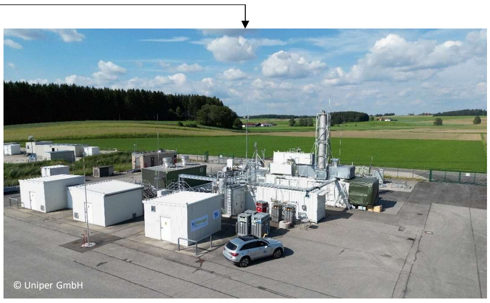
EUH2STARS
Type: Depleted Field
Commissioning: 2024

UGS Ptruka
Type: Depleted Field
Commissioning: 2025

H2I-S
Type: Depleted Field
Commissioning: 2023

Aquamarine
Type: Depleted Field
Commissioning: 2020

H2 Readiness
Type: Depleted Field
Commissioning: 2025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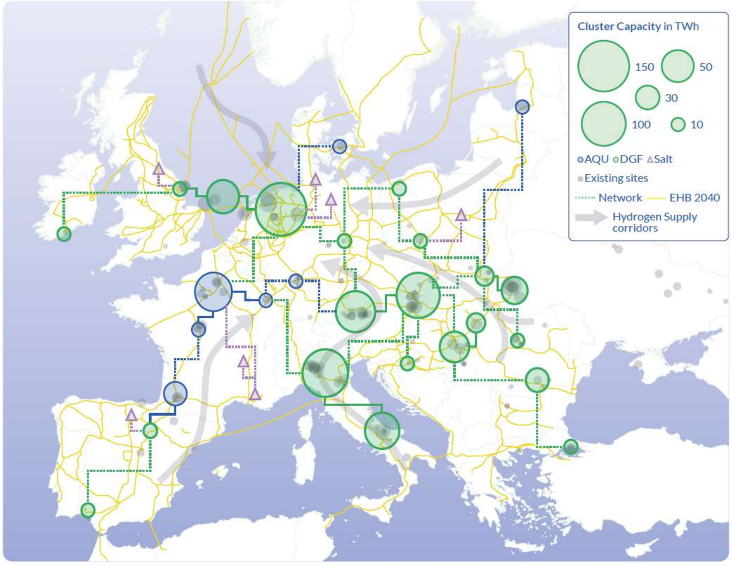
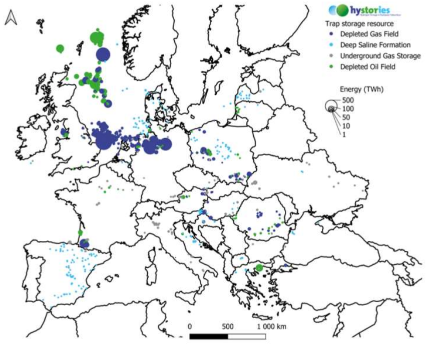
2050 vision of an integrated UHS infrastructure

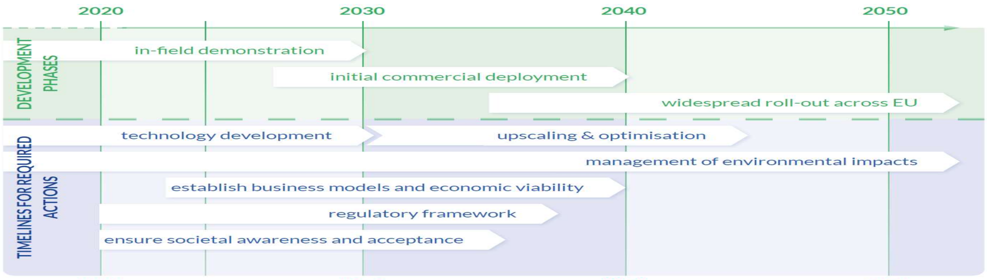
Illustrative vision of a H_2 storage infrastructure in 2050 that would include storage in porous reservoirs at 400 sites to fulfill a high storage demand of 1,000 TWh.

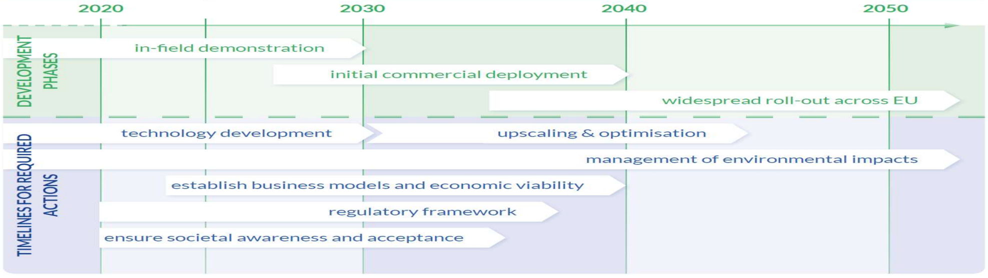


- ☐ 1200 TWh storage demand (high demand scenario)
- ☐ 150 TWh in converted UGS sites, 50 TWh in caverns
- ☐ 1000 TWh gap (High-Demand-Low-Supply scenario)
- ☐ Where to find this additional storage capacity?
  - In 400 sites, drawn at cluster level from shortlist
  - 70% of capacity provided by ≈ 30% of the sites
  - 90% of capacity by ≈ 50% of sites



Actions and timelines towards timely deployment



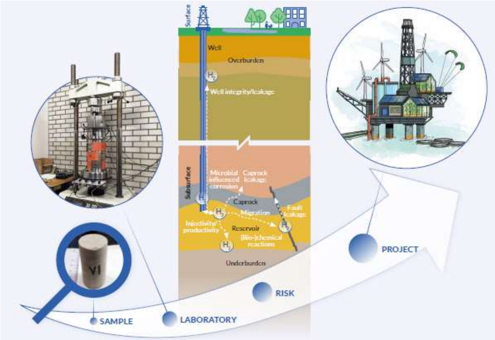


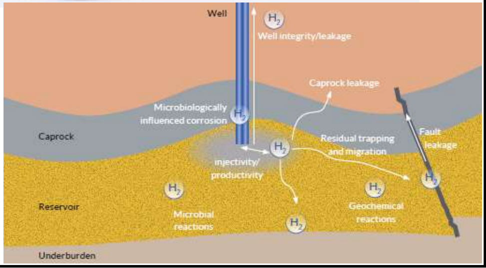
Anticipated timelines and required actions for upscaling UHS from its current readiness level at TRL 6 (reduced-scale in-field demonstrations) to TRL 8 (initial commercial deployment at full-scale) making it ready for widespread roll-out across the EU (TRL 9).

Technology development, upscaling and optimization

CONTINUE R&D ON QUANTIFYING UHS-RELEVANT SUBSURFACE PROCESSES

- Extend experimental testing to provide the proper basis for upscaling and implementation in models.
- Improve and integrate geological, thermodynamical geochemical, and microbiological models with reservoir flow models to improve capability to predict the produced fluid composition, including hydrogen purity and H_2S, as well as flow performance.
- Intensify data sharing, databases and open-source model development between research, industry and software service providers.
- Calibrate models with data from operational UHS sites.
- Extend existing global databases with UHS relevant data on microbiology, geochemistry, thermodynamics and geomechanics.





Technology development, upscaling and optimization

DEVELOP UHS-SPECIFIC COMPRESSION AND GAS CLEANING, AND HYDROGEN-COMPLIANT WELLS AND MATERIALS

- Upscale compression technologies to handle large flow rates efficienty to reduce footprint and weight.
- Develop innovative purification solutions for H_2 and tail gas
- Develop H_2-compatible wells & materials for corrosive, wet conditions.
- Implement semi-commercial UHS projects that can develop market-ready storage solutions and optimise them for further scale-up.
- Develop processes for circularity materials, equipment, infrastructure.

DEVELOP UHS-SPECIFIC OPERATING STANDARDS AND MONITORING TECHNOLOGIES

- Develop standards for material selection, well design, facilities design, and operational practices for UHS sites.
- Develop MMV technologies for safe UHS operation through continued R&D pilots and demonstrations.
- Assess suitability of existing monitoring techniques from UGS and supplement these with techniques needed specifically for UHS.
- Develop abandonment standards.

Managing environmental impacts

Ensure integrity, mitigate leakage risk

- Identify risks and develop best practices to mitigate them.
- Establish threshold values for monitoring environmental impact based on the experience from existing pilots and analogous applications.
- Develop a catalogue of best practices and standards to mitigate and monitor hydrogen leakage risk and safeguard long-term integrity.
- Stimulate worldwide sharing of experience.

Demonstrate safety and minimise environmental impact

- Establish legal requirements, standards, and unified guidelines for monitoring of environmental effects of UHS sites.
- Implement monitoring plans to evaluate (long-term) effects of UHS sites on the environment and demonstrate safety, conformance and compliance.
- Continuously improve technologies and practices for construction and operation to reduce emissions while maximising process efficiency, thus minimising environmental impact and footprint.

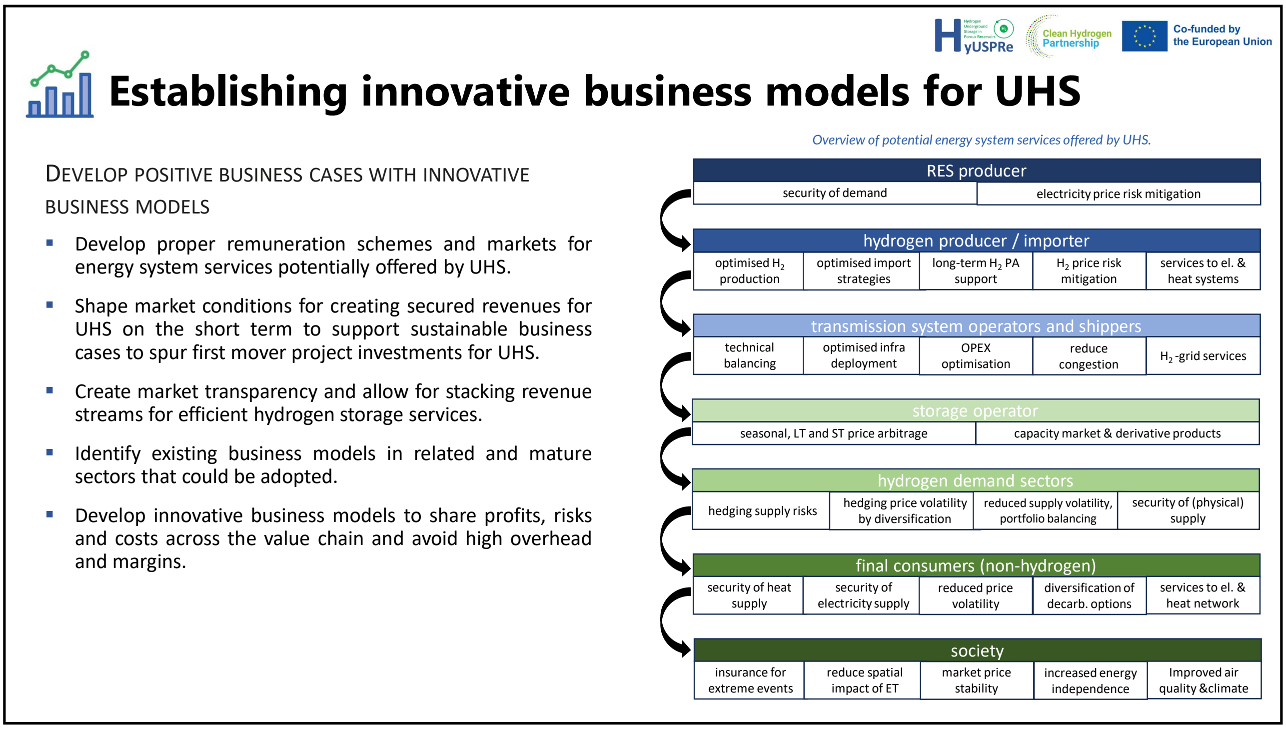
Establishing economic viability

Facilitate development of a H_2 storage market

- Prevent market failure and establish clear strategies to leverage the energy system value of storage of UHS.
- Develop pre-financing & derisking strategies for storage infrastructure build-up in the pre-commercial era of UHS.
- Shape market conditions for UHS before the onset of wide-scale hydrogen market development in Europe
- Provide a clear outlook for the envisioned market transition from pre-commercial to commercial and mature market phases of UHS.

Overcome cost-related challenges

- Develop public-private cost sharing and reliable financing incentives for pioneer UHS projects
- Stimulate innovation to achieve cost reduction and cost efficiency for UHS scale-up in porous media.
- Work towards early standardisation to reduce capital, operating and financing cost.
- Facilitate roll-out and replicable learnings of a portfolio of demonstration projects to build trust, improve market readiness and establish bankable UHS projects.



Co-funded by the European Union

Establishing innovative business models for UHS

DEVELOP POSITIVE BUSINESS CASES WITH INNOVATIVE BUSINESS MODELS

- Develop proper remuneration schemes and markets for energy system services potentially offered by UHS.
- Shape market conditions for creating secured revenues for UHS on the short term to support sustainable business cases to spur first mover project investments for UHS.
- Create market transparency and allow for stacking revenue streams for efficient hydrogen storage services.
- Identify existing business models in related and mature sectors that could be adopted.
- Develop innovative business models to share profits, risks and costs across the value chain and avoid high overhead and margins.

Overview of potential energy system services offered by UHS.

RES producer
- security of demand
- electricity price risk mitigation

hydrogen producer / importer
- optimised H_2 production
- optimised import strategies
- long-term H_2 PA support
- H_2 price risk mitigation
- services to el. & heat systems

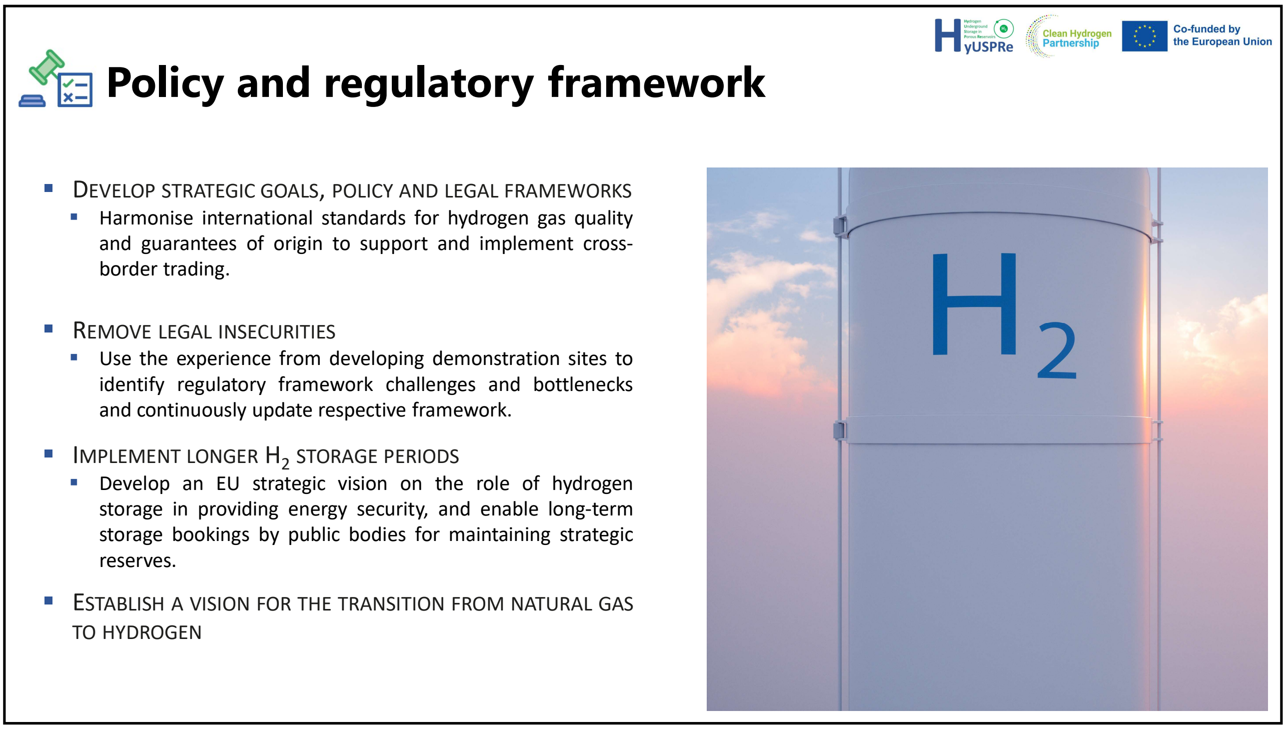
transmission system operators and shippers
- technical balancing
- optimised infra deployment
- OPEX optimisation
- reduce congestion
- H_2-grid services

storage operator
- seasonal, LT and ST price arbitrage
- capacity market & derivative products

hydrogen demand sectors
- hedging supply risks
- hedging price volatility by diversification
- reduced supply volatility, portfolio balancing
- security of (physical) supply

final consumers (non-hydrogen)
- security of heat supply
- security of electricity supply
- reduced price volatility
- diversification of decarb. options
- services to el. & heat network

society
- insurance for extreme events
- reduce spatial impact of ET
- market price stability
- increased energy independence
- Improved air quality &climate



Co-funded by the European Union

Policy and regulatory framework

- DEVELOP STRATEGIC GOALS, POLICY AND LEGAL FRAMEWORKS
  - Harmonise international standards for hydrogen gas quality and guarantees of origin to support and implement cross-border trading.
- REMOVE LEGAL INSECURITIES
  - Use the experience from developing demonstration sites to identify regulatory framework challenges and bottlenecks and continuously update respective framework.
- IMPLEMENT LONGER H_2 STORAGE PERIODS
  - Develop an EU strategic vision on the role of hydrogen storage in providing energy security, and enable long-term storage bookings by public bodies for maintaining strategic reserves.
- ESTABLISH A VISION FOR THE TRANSITION FROM NATURAL GAS TO HYDROGEN

Societal awareness and acceptance

- Increase general public awareness on hydrogen
  - Conduct positive, user-driven information campaigns on hydrogen technologies through various media and information channels.
- Develop educational measures on UHS and H_2
- Develop information campaigns on local to EU- level
  - Conduct objective information campaigns on awareness regarding UHS in porous reservoirs for policy makers at various levels, initiated by industry and research.
- Establish benefits sharing, form energy communities
  - Foster local value creation by including local suppliers, cooperations, build-up of local workforce or through sponsorship of local community projects.

HyUSPRe's Call to Action

Call to Action

Technology development

- Develop UHS-tailored technologies for compression, gas cleaning, wells and materials
- Continue R&D on subsurface processes and development of reservoir models and software
- Develop UHS-specific monitoring technologies

Environmental impact and spatial planning

- Ensure integrity and mitigate leakage risk
- Implement monitoring plans for UHS in porous reservoirs
- Demonstrate safety and minimise environmental impact
- Develop a land use plan in line with the energy transition
- Develop appropriate regulations and standards for UHS in porous reservoirs

Economics and market

- Facilitate development of a hydrogen market
- Overcome cost-related challenges
- Develop positive business cases with innovative business models

- Increase public awareness
- Develop educational measures for use in schools
- Develop information measures from local to European politics
- Learn from stakeholder perspectives to improve

Call to Action

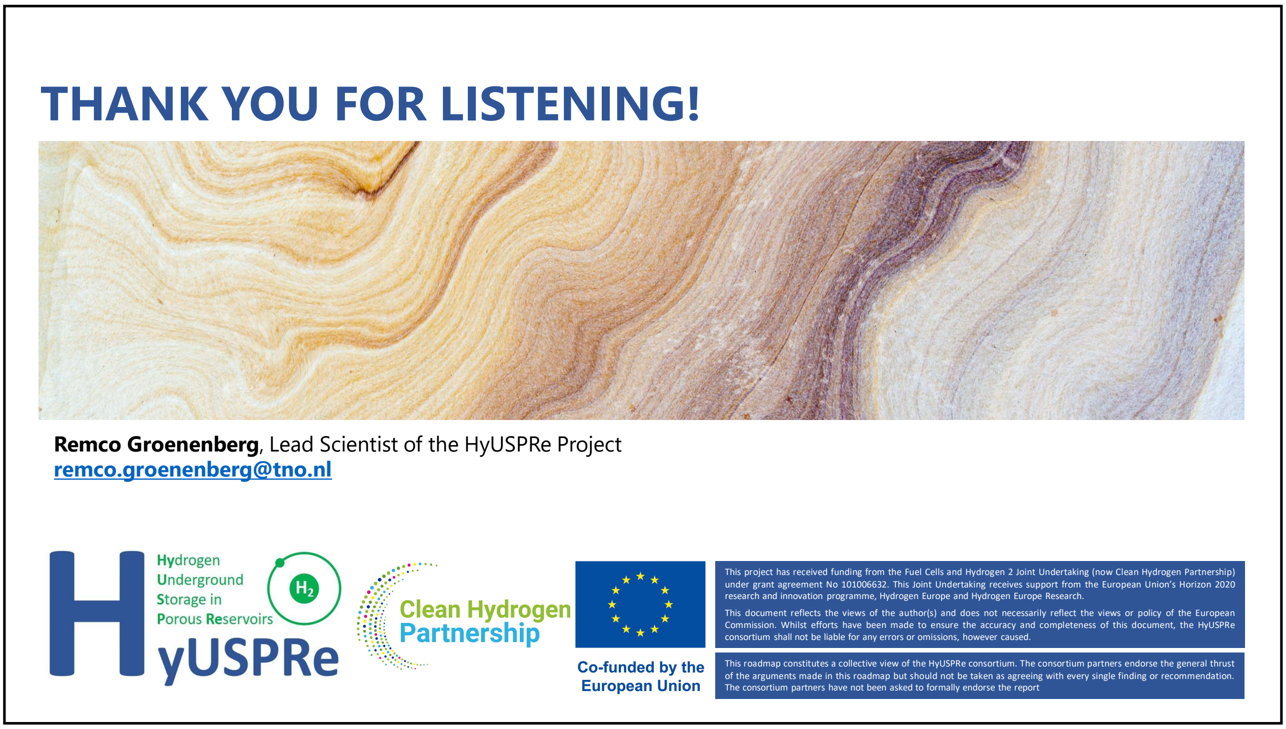
- Facilitate development of a hydrogen market
- Overcome cost-related challenges
- Develop positive business cases with innovative business models

Societal awareness and acceptance

- Increase public awareness
- Develop educational measures for use in schools
- Develop information measures from local to European politics
- Learn from stakeholder perspectives to improve design, planning and operation
- Facilitate engagement of direct neighbours and energy communities

Policy and regulation

- Develop strategic goals, policy and legal framework
- Remove legal insecurities
- Implement longer hydrogen storage periods and adjust certification framework
- Use this roadmap to develop a step-wise-plan for transitioning from natural gas to hydrogen



THANK YOU FOR LISTENING!

Remco Groenenberg, Lead Scientist of the HyUSPRe Project
remco.groenenberg@tno.nl

Hydrogen
Underground
Storage in
Porous Reservoirs
HyUSPRe

Clean Hydrogen
Partnership

Co-funded by the
European Union

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.

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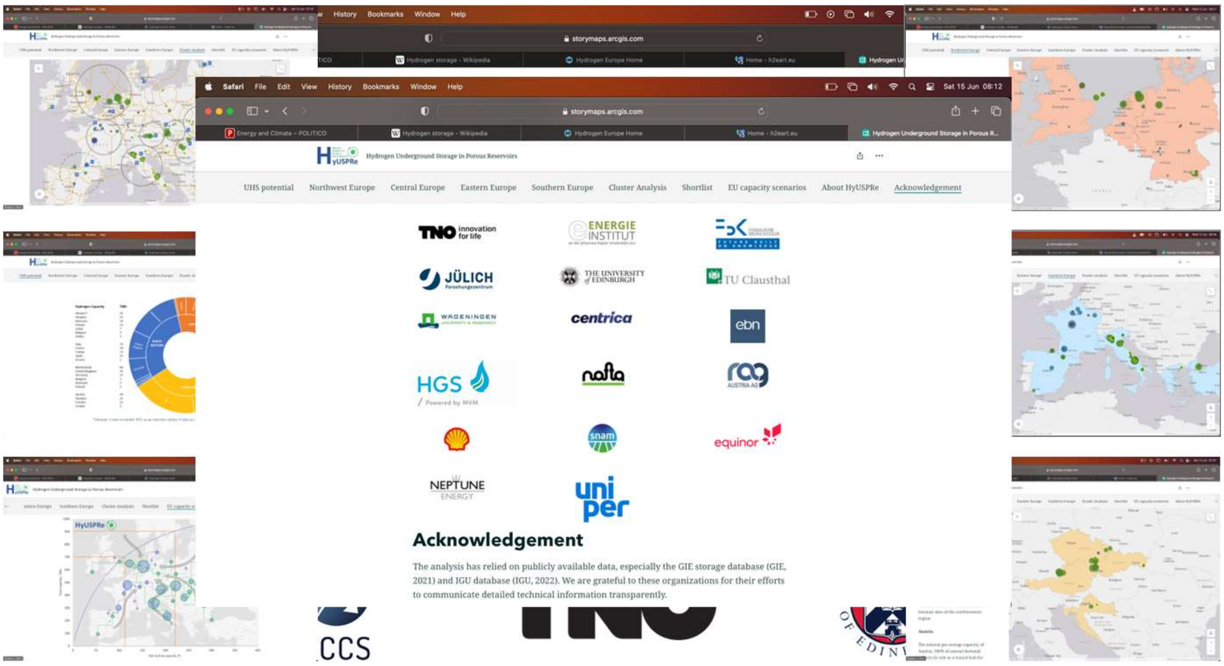
This roadmap constitutes a collective view of the HyUSPRe consortium. The consortium partners endorse the general thrust of the arguments made in this roadmap but should not be taken as agreeing with every single finding or recommendation. The consortium partners have not been asked to formally endorse the report

Hydrogen storage assessments and implemenation scenarios

[04] What the HyUSPRe hydrogen storage story maps tell us (*Andrew Cavanagh*, University of Edinburgh)

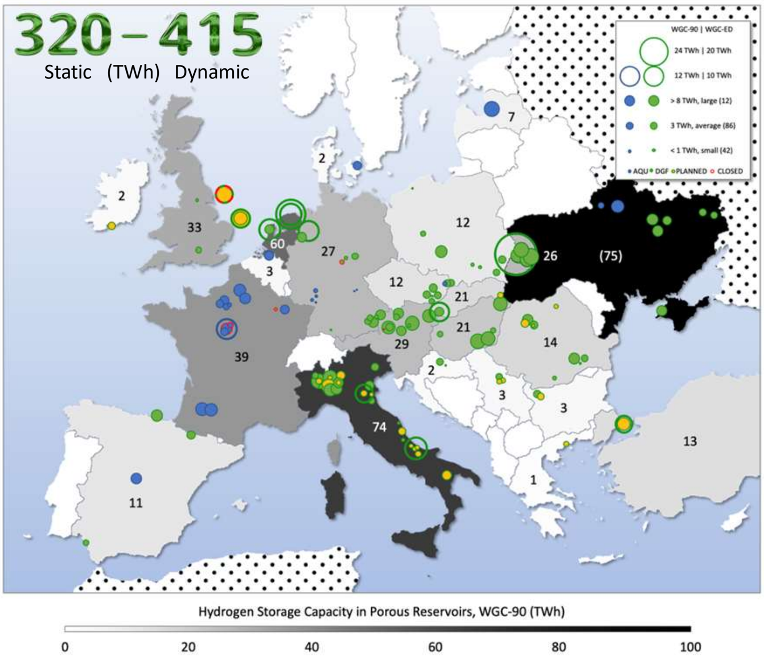


Acknowledgement

The analysis has relied on publicly available data, especially the GIE storage database (GIE, 2021) and IGU database (IGU, 2022). We are grateful to these organizations for their efforts to communicate detailed technical information transparently.

320 – 415

Static (TWh) Dynamic



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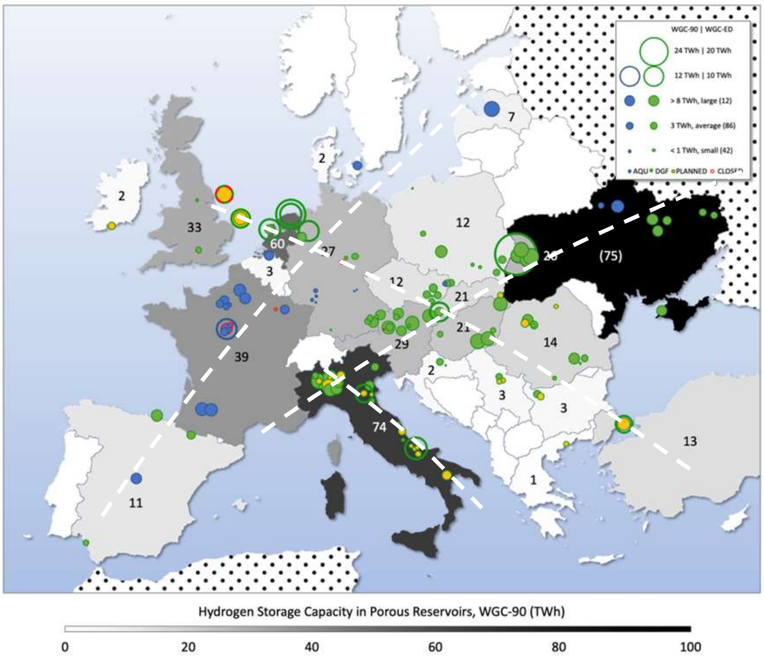

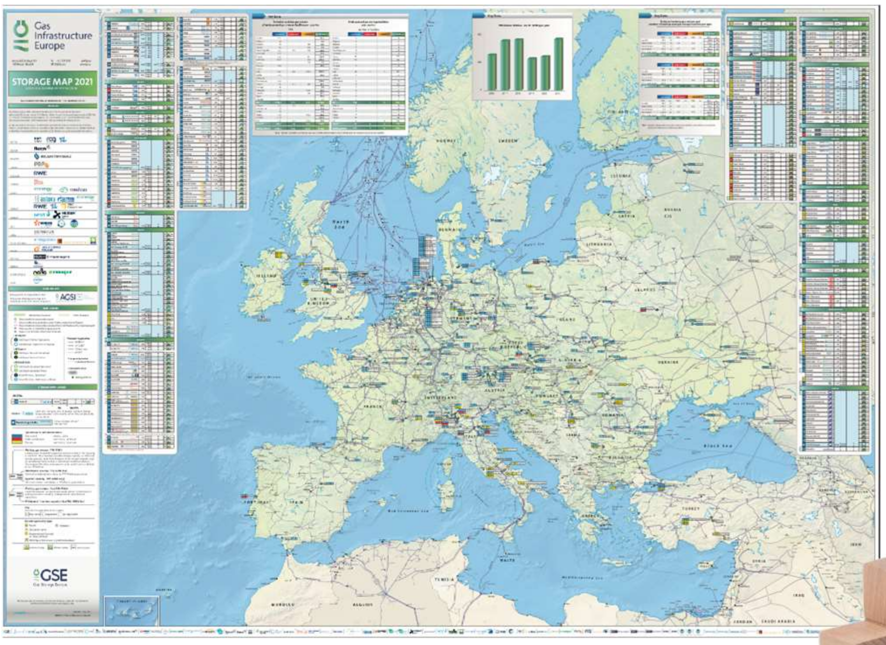

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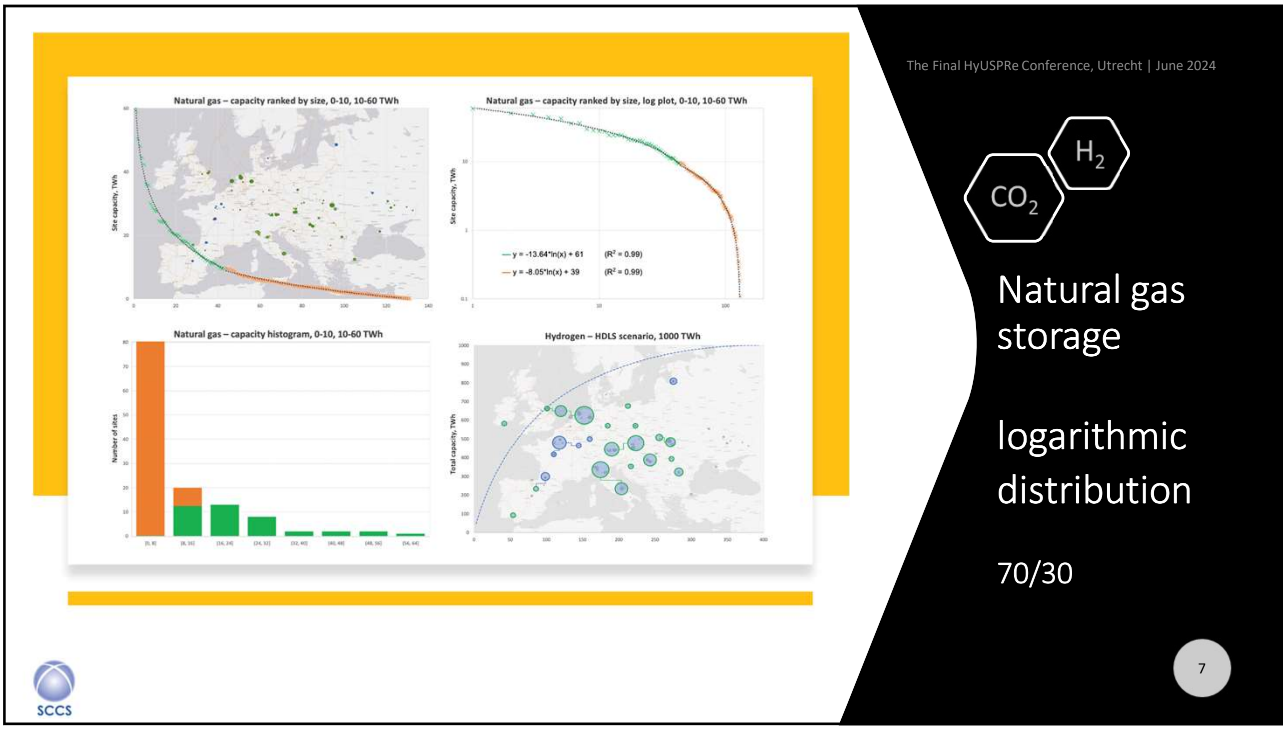
SCCS



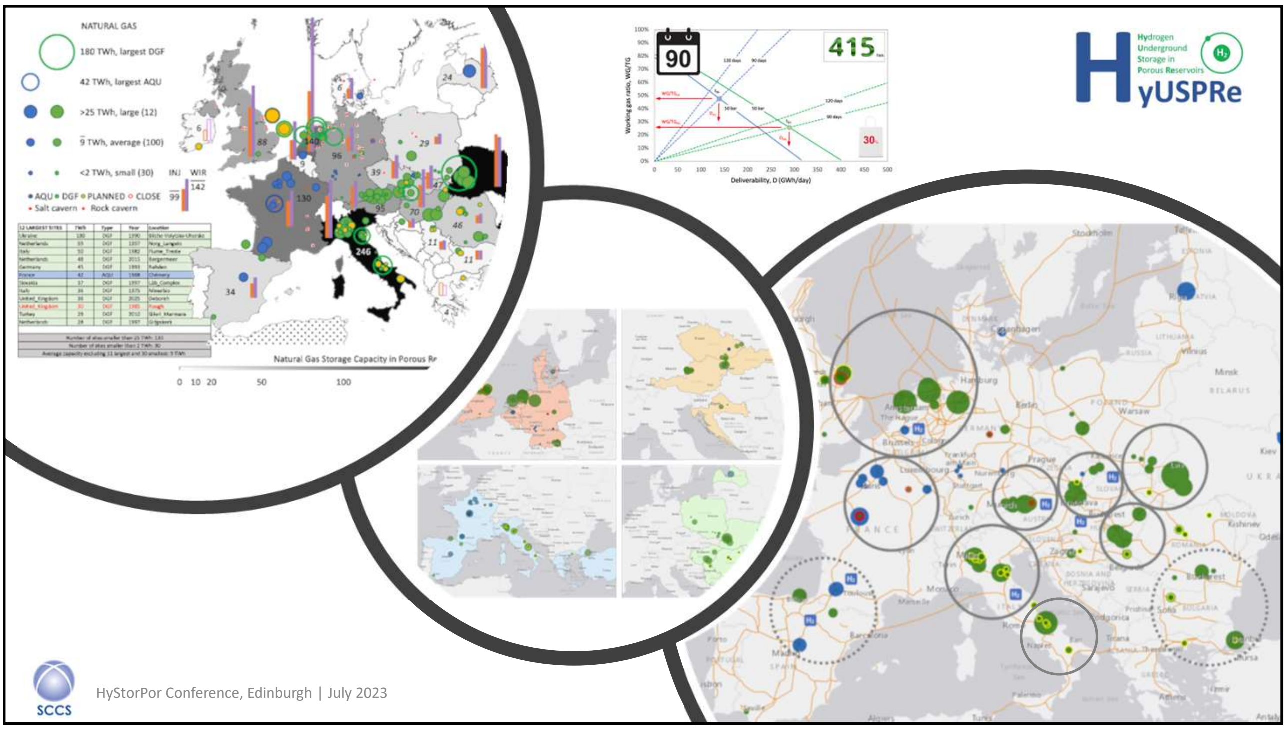
The Final HyUSPRe Conference, Utrecht | June 2024

CO_2 H_2

Natural gas storage

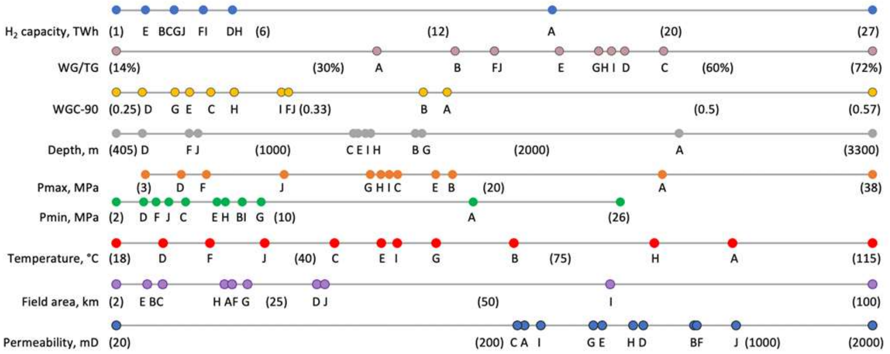
logarithmic distribution

70/30



SCCS HyStorPor Conference, Edinburgh | July 2023

HyStorPor Conference, Edinburgh | July 2023

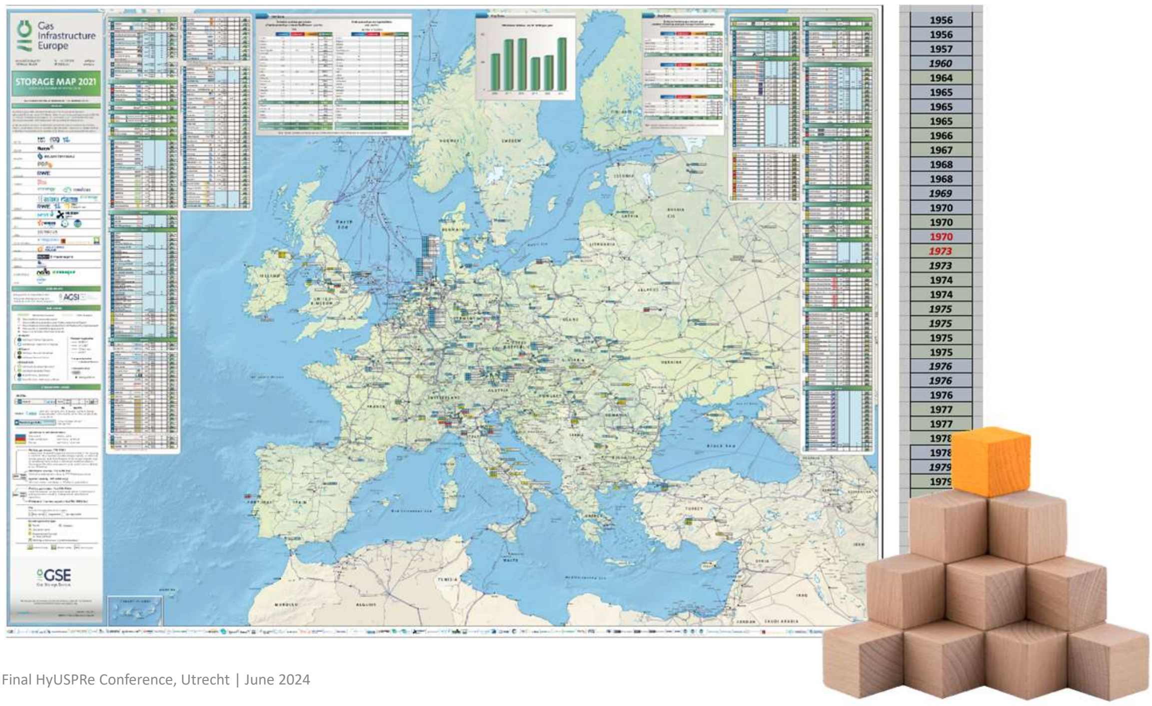


Capacity: 1-5 TWh
Working gas: 30% - 60%
Conversion factor: ¼ - ⅓

Pmax: 5-20 MPa
Pmin: 3-10 Mpa

Depth: 500-1500m
Temp: 20-100 °C
Field area: 3-30 km^2
Perm: 200-1000 mD

Cavanagh et al 2023 | Report: hyuspre.eu/downloads/report/D1.3



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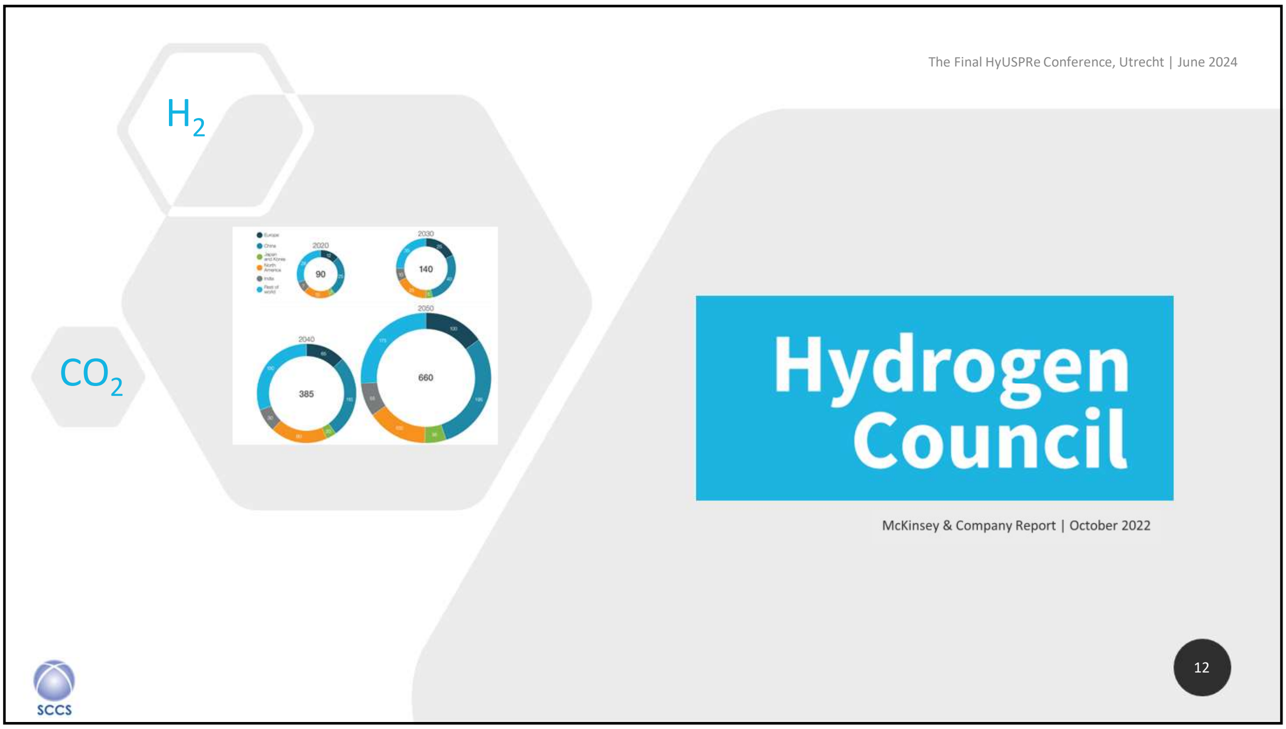

The Final HyUSPRe Conference, Utrecht | June 2024

Hydrogen Council

McKinsey & Company Report | October 2022

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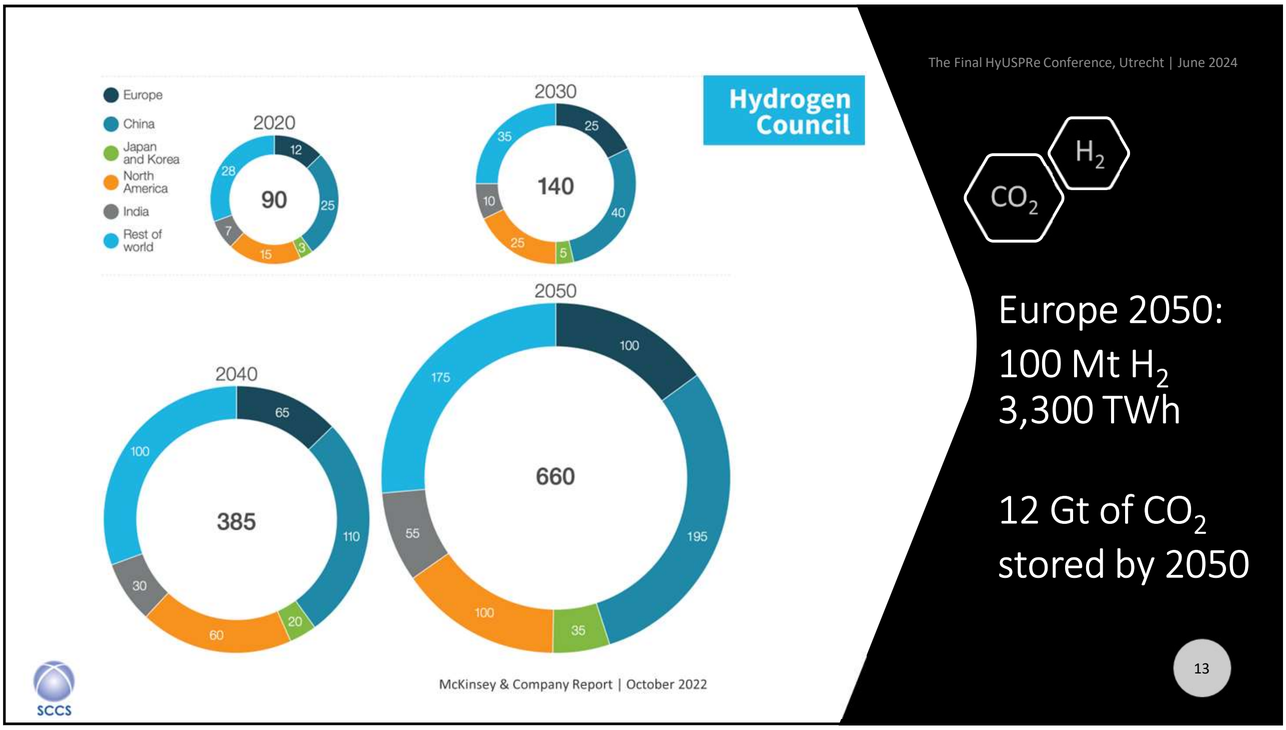


Hydrogen Council

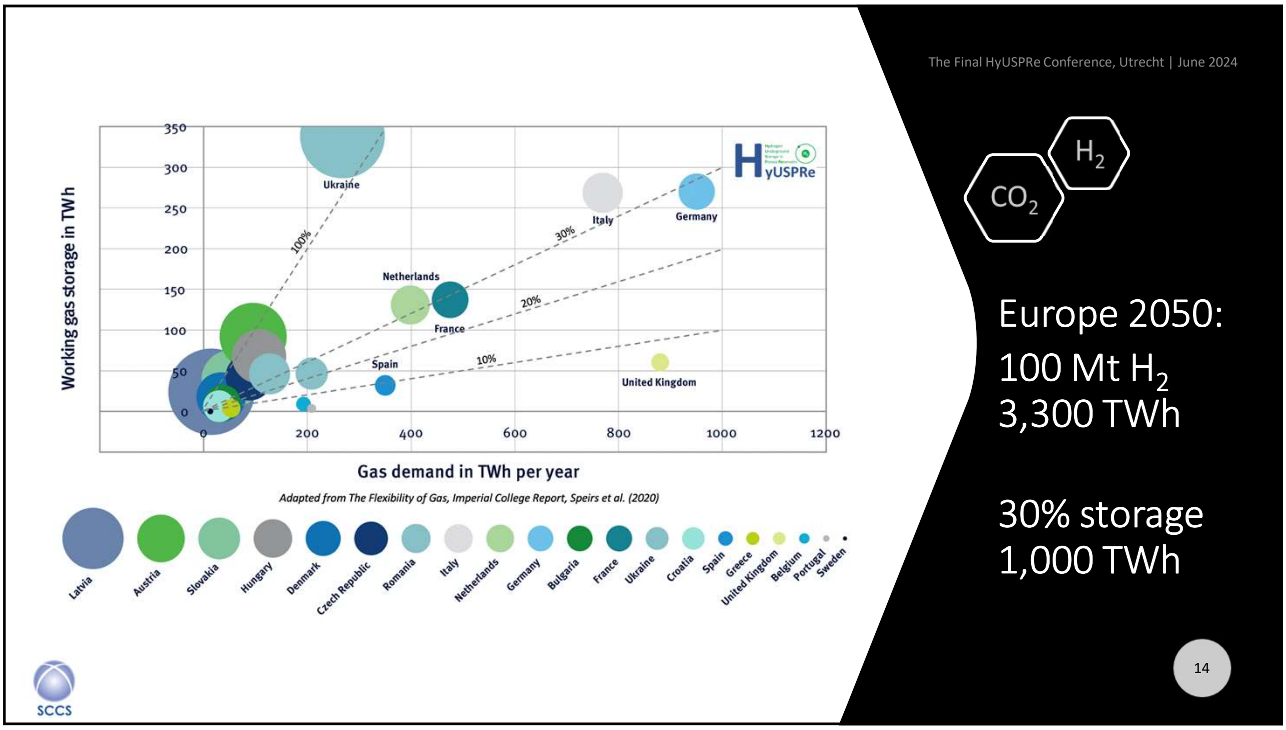
McKinsey & Company Report | October 2022

The Final HyUSPRe Conference, Utrecht | June 2024

Europe 2050:
100 Mt H_2
3,300 TWh

12 Gt of CO_2
stored by 2050

13



Adapted from The Flexibility of Gas, Imperial College Report, Speirs et al. (2020)

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Europe 2050:
100 Mt H_2
3,300 TWh

30% storage
1,000 TWh

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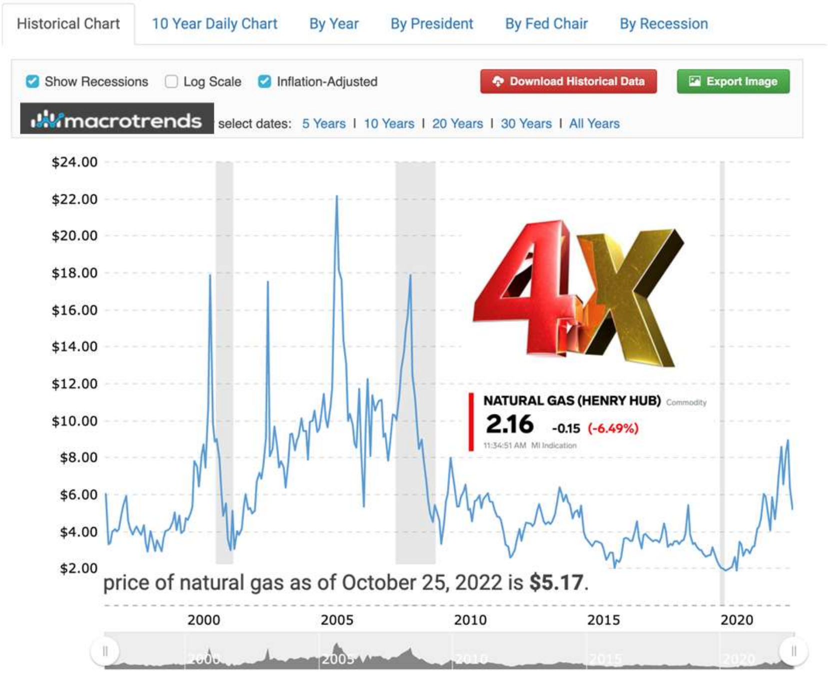
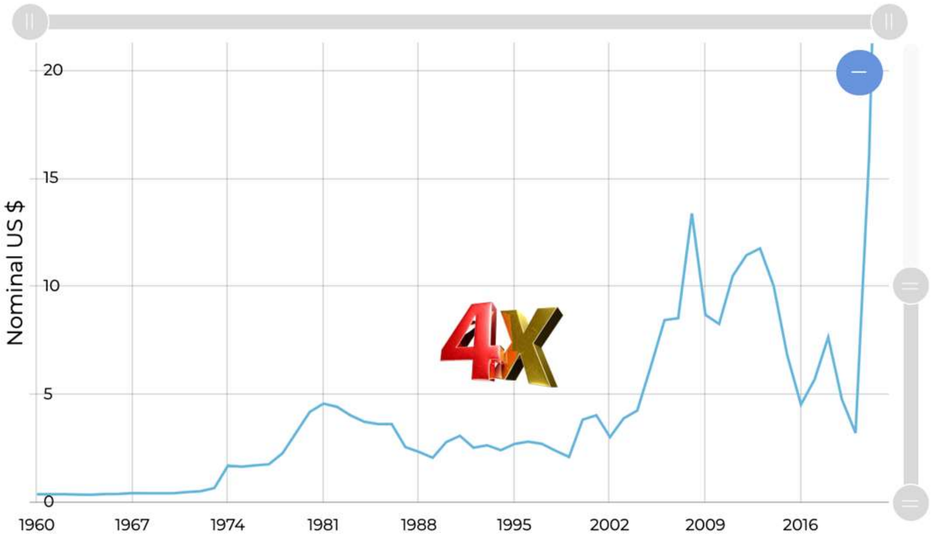


price of natural gas as of October 25, 2022 is **$5.17**.

World Bank Annual Europe Natural Gas Price in Nominal US $



Financial Times
June 2023

EU turns to Africa to build green hydrogen supply

The bloc insists the proposal is mutually beneficial for Europe and Africa, but critics accuse it of resource grabbing

High potential: producing green hydrogen requires a lot of energy, and Africa is well placed to provide cheap solar power © Fadel Senna/AFP via Getty Images

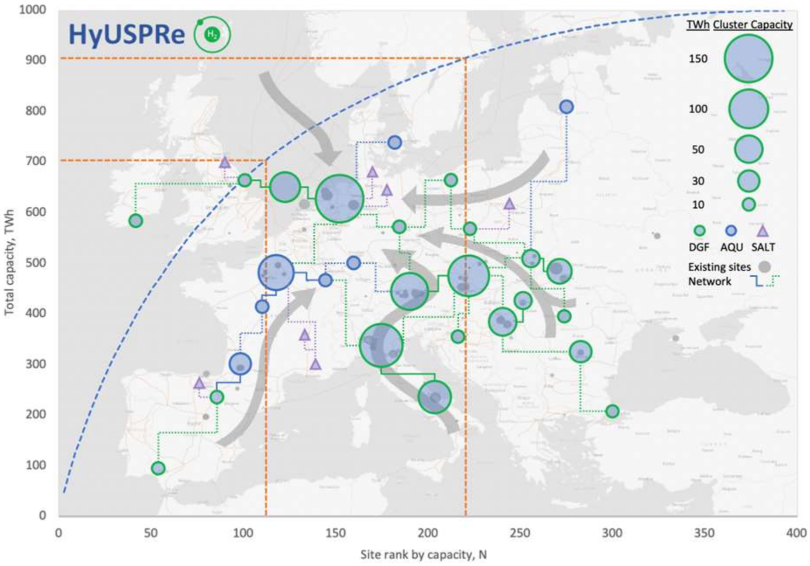
Philippa Nuttall JUNE 15 2023

Europe has set an ambitious target of producing 10mn tonnes of renewable-based hydrogen by 2030, and importing the same amount — and, as so many times before, it is looking to Africa to supply the resources it needs.

What the HyUSPRe hydrogen storage StoryMap tells us

Andrew Cavanagh, Hamid Yousefi, Mark Wilkinson, Remco Groenenberg

The Final HyUSPRe Conference, Utrecht | June 2024



Cavanagh et al 2023 | Report: hyuspre.eu/downloads/report/D1.3

HyStorPor Conference, ECCI, Edinburgh 12 July 2023

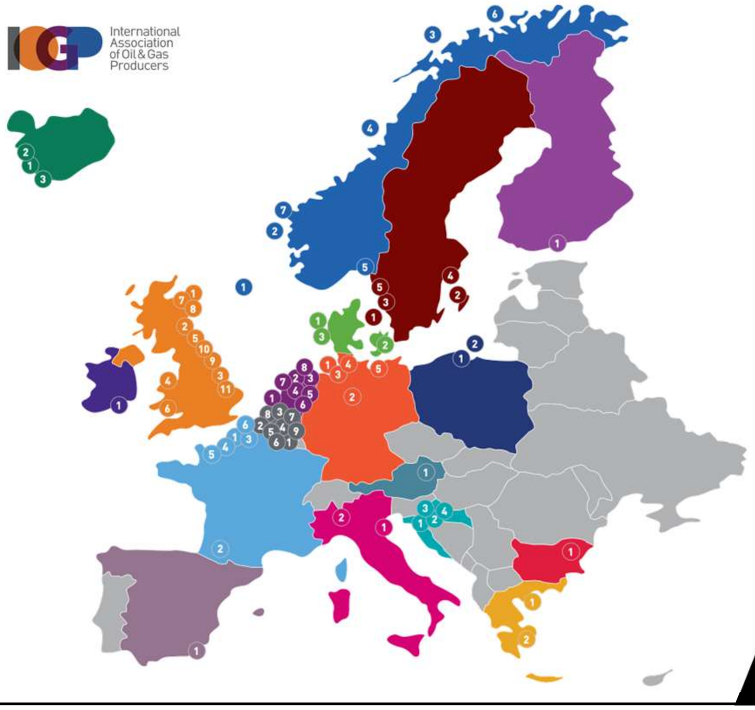
CO_2 H_2

1,000 TWh

80% gas fields
10% aquifers
10% salt caverns
120 sites, 3-9 TWh
130 sites, 1-3 TWh
150 sites < 1 TWh

International Association of Oil & Gas Producers

IOGP 2023 | Report: iogpeurope.org/uploads/map_of_eu_ccus



H_2

CO_2

CCS 2030: 80 Mt/yr

72 projects
50 North Sea

Hydrogen storage assessments and implemenation scenarios

[05] Techno-economic assessment of EU scale hydrogen system scenarios (*Theresa Groß*, Forschungszentrum Jülich)

HYUSPRE
TECHNO-ECONOMIC ASSESSMENT OF EU SCALE HYDROGEN SYSTEM SCENARIOS

THERESA GROSS|
FORSCHUNGSZENTRUM JÜLICH, IEK-3

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.

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OUTLINE

- Background
- Modeling Approach & Scenario Definitions
- Modeling Results: Baseline Scenarios
- Modeling Results: Sensitivities
- Conclusions

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EU-SCALE HYDROGEN SYSTEM MODELING

Objective: Assessing the potential **role of hydrogen storages** in porous reservoirs within a future European hydrogen system

Approach:
- Model: European energy system optimization model ETHOS.Europe (EU27 + UK + NO + CH)
- Target of the optimization: Minimization of the total annual cost while considering technical and environmental constraints.
- Scenarios: 18 different scenario configurations for 2030, 2040, 2050 (in total, 54 scenarios)

Results:
- Total storage volume capacities for hydrogen storage (TWh)
- Storage operation, and maximum injection and withdrawal capacities
- Number of storage cycles
- Electricity, natural gas and hydrogen infrastructure

Results will be published in deliverable D7.2 (https://www.hyuspre.eu/index.php/downloads/):
T. Groß, P. Dunkel et al. (2024): Report on the EU-scale hydrogen system scenarios, H2020 HyUSPRe project report. 80 pp + appendices.

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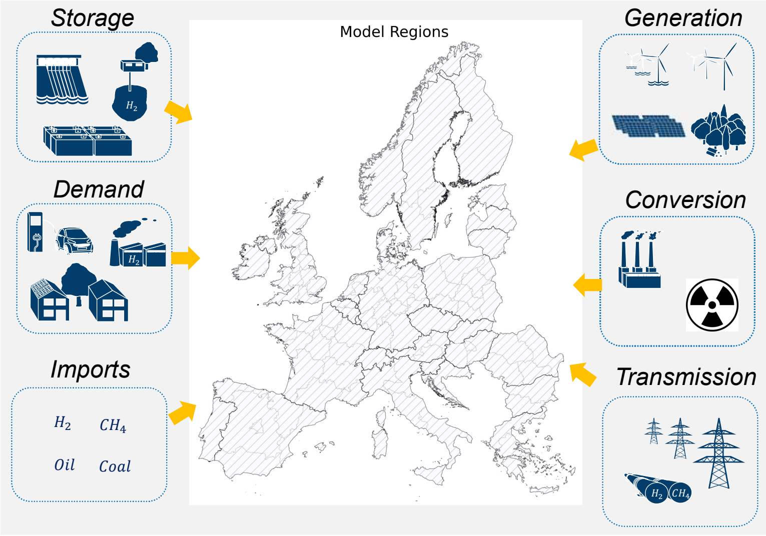
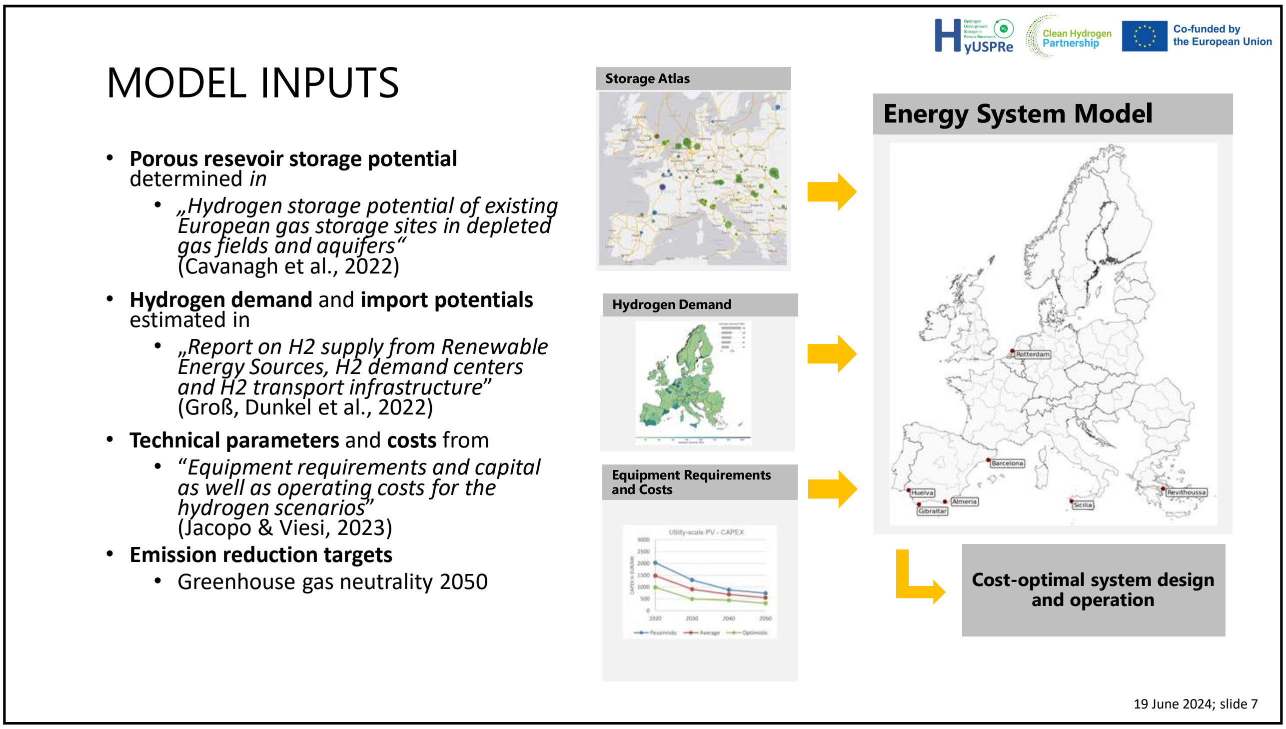
MODEL SCOPE

- **Spatial Scope**:
  - EU 27 + United Kingdom, Norway & Switzerland
  - onshore-regions:
    - 100 (NUTS-1)
  - offshore-regions:
    - 76
- **Temporal Scope**
  - 2030, 2040, 2050
  - hourly resolution
- The model is implemented using the open-source python package ETHOS.FINE [1] and aims to minimize the total annual costs.

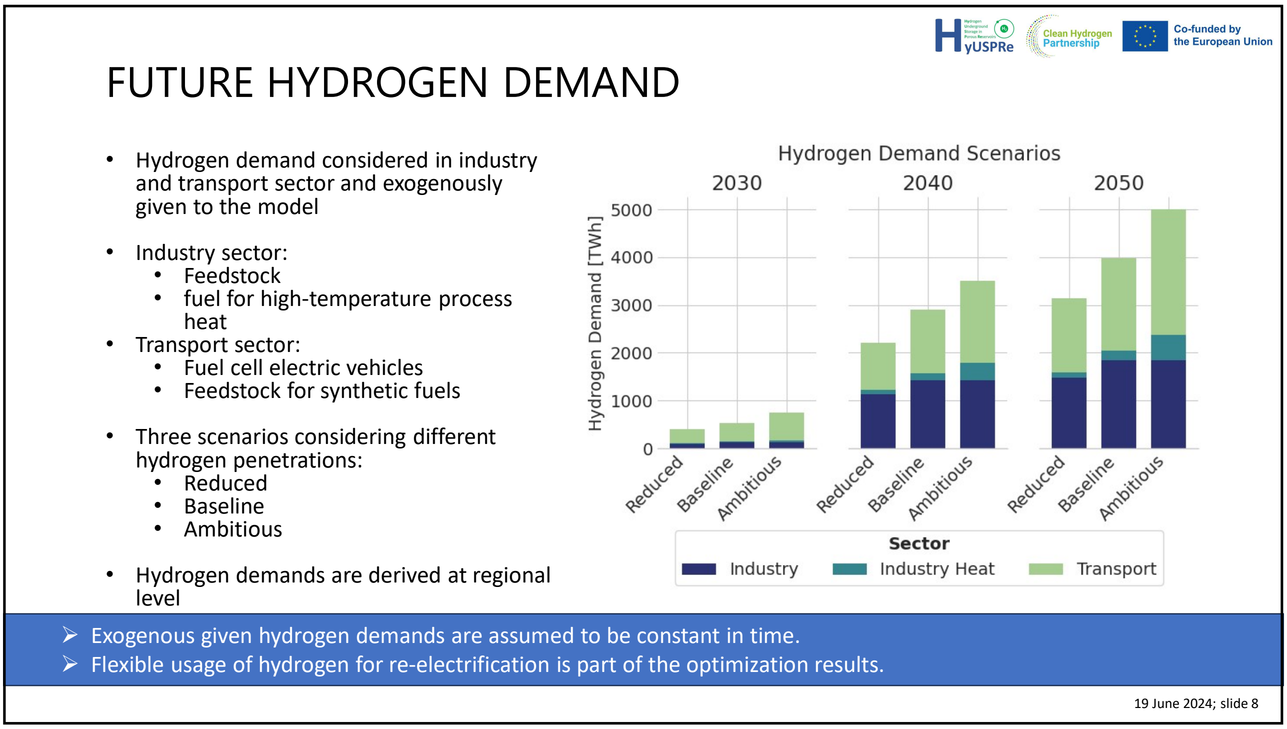


[1] Framework for Integrated Energy Systems Assessment: https://github.com/FZJ-IEK3-VSA/FINE



MODEL INPUTS

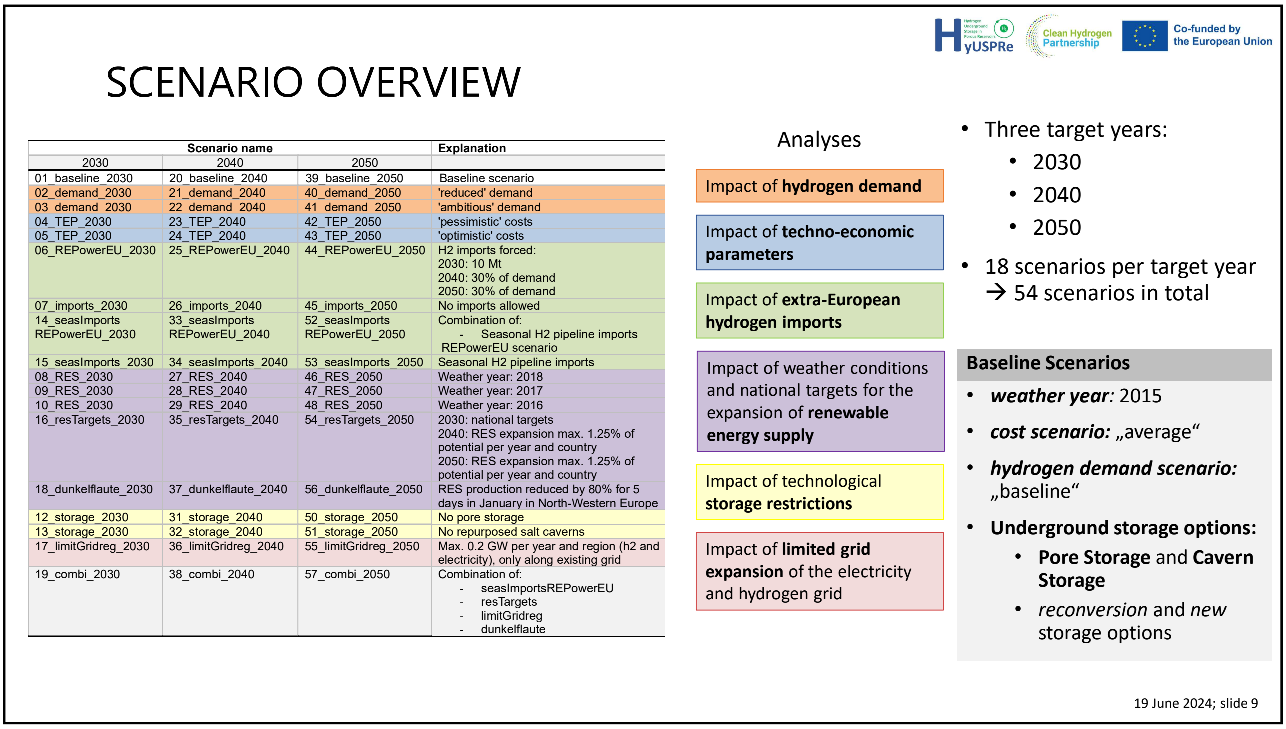
- **Porous resevoir storage potential** determined *in*
  - *„Hydrogen storage potential of existing European gas storage sites in depleted gas fields and aquifers“* (Cavanagh et al., 2022)
- **Hydrogen demand** and **import potentials** estimated in
  - *„Report on H2 supply from Renewable Energy Sources, H2 demand centers and H2 transport infrastructure”* (Groß, Dunkel et al., 2022)
- **Technical parameters** and **costs** from
  - *“Equipment requirements and capital as well as operating costs for the hydrogen scenarios”* (Jacopo & Viesi, 2023)
- **Emission reduction targets**
  - Greenhouse gas neutrality 2050



FUTURE HYDROGEN DEMAND

- Hydrogen demand considered in industry and transport sector and exogenously given to the model
- Industry sector:
  - Feedstock
  - fuel for high-temperature process heat
- Transport sector:
  - Fuel cell electric vehicles
  - Feedstock for synthetic fuels
- Three scenarios considering different hydrogen penetrations:
  - Reduced
  - Baseline
  - Ambitious
- Hydrogen demands are derived at regional level

- ➢ Exogenous given hydrogen demands are assumed to be constant in time.
- ➢ Flexible usage of hydrogen for re-electrification is part of the optimization results.



SCENARIO OVERVIEW

Scenario name			Explanation
2030	2040	2050	
01_baseline_2030	20_baseline_2040	39_baseline_2050	Baseline scenario
02_demand_2030	21_demand_2040	40_demand_2050	'reduced' demand
03_demand_2030	22_demand_2040	41_demand_2050	'ambitious' demand
04_TEP_2030	23_TEP_2040	42_TEP_2050	'pessimistic' costs
05_TEP_2030	24_TEP_2040	43_TEP_2050	'optimistic' costs
06_REPowerEU_2030	25_REPowerEU_2040	44_REPowerEU_2050	H2 imports forced: 2030: 10 Mt 2040: 30% of demand 2050: 30% of demand
07_imports_2030	26_imports_2040	45_imports_2050	No imports allowed
14_seasImports REPowerEU_2030	33_seasImports REPowerEU_2040	52_seasImports REPowerEU_2050	Combination of: - Seasonal H2 pipeline imports REPowerEU scenario
15_seasImports_2030	34_seasImports_2040	53_seasImports_2050	Seasonal H2 pipeline imports
08_RES_2030	27_RES_2040	46_RES_2050	Weather year: 2018
09_RES_2030	28_RES_2040	47_RES_2050	Weather year: 2017
10_RES_2030	29_RES_2040	48_RES_2050	Weather year: 2016
16_resTargets_2030	35_resTargets_2040	54_resTargets_2050	2030: national targets 2040: RES expansion max. 1.25% of potential per year and country 2050: RES expansion max. 1.25% of potential per year and country
18_dunkelflaute_2030	37_dunkelflaute_2040	56_dunkelflaute_2050	RES production reduced by 80% for 5 days in January in North-Western Europe
12_storage_2030	31_storage_2040	50_storage_2050	No pore storage
13_storage_2030	32_storage_2040	51_storage_2050	No repurposed salt caverns
17_limitGridreg_2030	36_limitGridreg_2040	55_limitGridreg_2050	Max. 0.2 GW per year and region (h2 and electricity), only along existing grid
19_combi_2030	38_combi_2040	57_combi_2050	Combination of: - seasImportsREPowerEU - resTargets - limitGridreg - dunkelflaute

Analyses

Impact of **hydrogen demand**

Impact of **techno-economic parameters**

Impact of **extra-European hydrogen imports**

Impact of weather conditions and national targets for the **expansion of renewable energy supply**

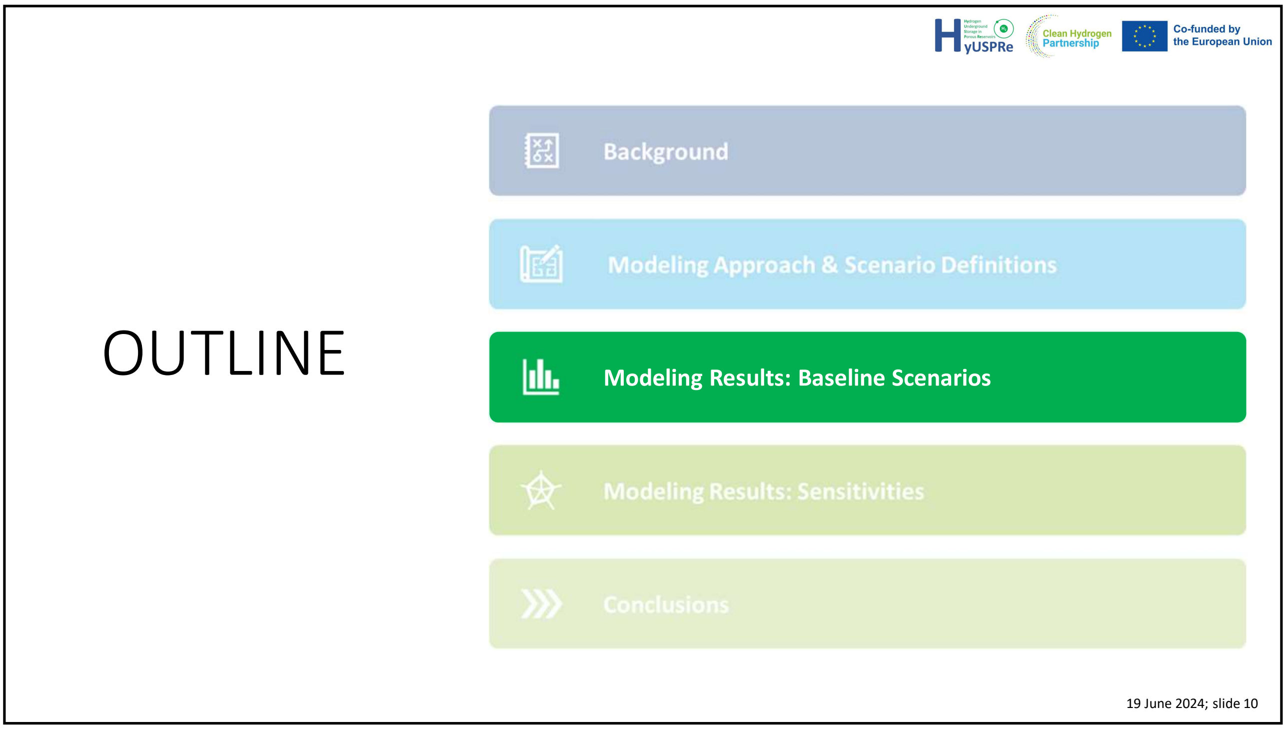
Impact of technological **storage restrictions**

Impact of **limited grid expansion** of the electricity and hydrogen grid

- Three target years:
  - 2030
  - 2040
  - 2050
- 18 scenarios per target year
  → 54 scenarios in total

Baseline Scenarios

- ***weather year***: 2015
- ***cost scenario:*** „average“
- ***hydrogen demand scenario:*** „baseline“
- **Underground storage options:**
  - **Pore Storage** and **Cavern Storage**
  - *reconversion* and *new* storage options



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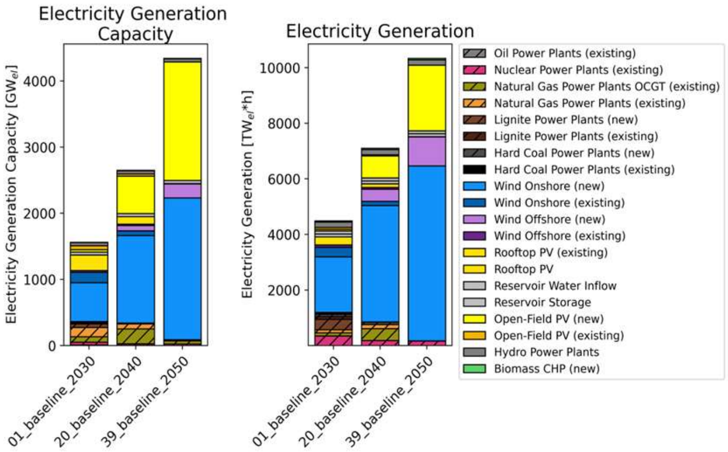
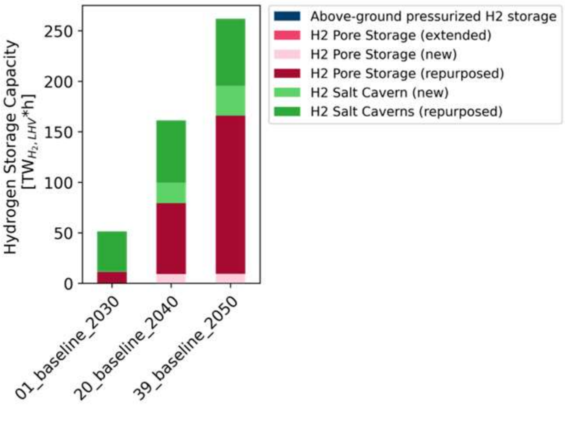
BASELINE SCENARIOS: ELECTRICITY MIX

- The electricity mix is part of the optimization results.
- Reduction targets of the greenhouse gas emissions are given as input.
- Onshore wind power emerges as the primary source of electricity generation (> 60% in 2050).
- By 2050, all conventional power plants have been phased out in accordance with established emission limits.
- Re-electrification of hydrogen is neglible due to the high share of renewable energy technologies and investments in electricity transmission infrastructure.

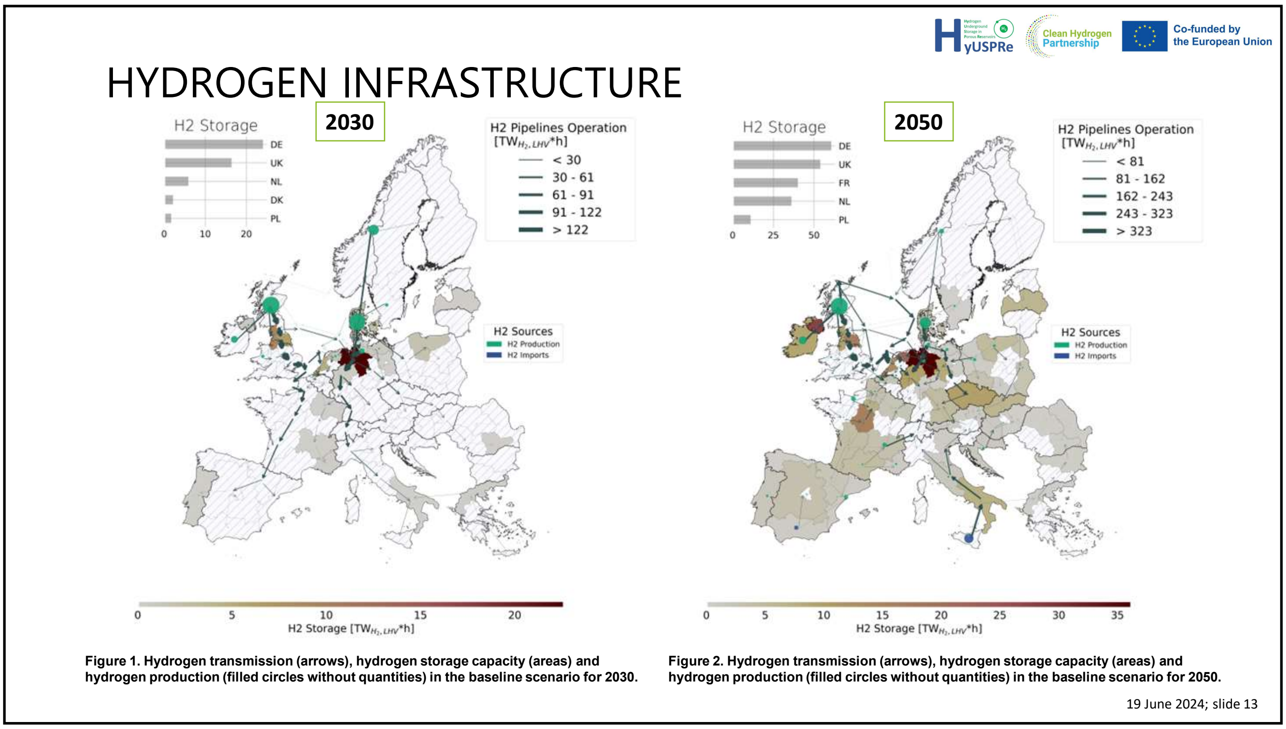


HYDROGEN STORAGE CAPACITY

- By 2050, about 260 TWh of hydrogen storage capacity is required to match supply and demand.
- Pore storage become an important storage option starting in 2040, after all existing salt caverns were repurposed for hydrogen storage.
- In 2050, pore storage constitutes more than 60% of the optimal storage capacity.
- The results are consistent with the recent study of Artelys and frontier economics [1] which is used by the EU-wide alliance H2eart for Europe.
  - Observed deviations in hydrogen storage capacity and injection capacity are only around 10%, both in 2030 and 2050.



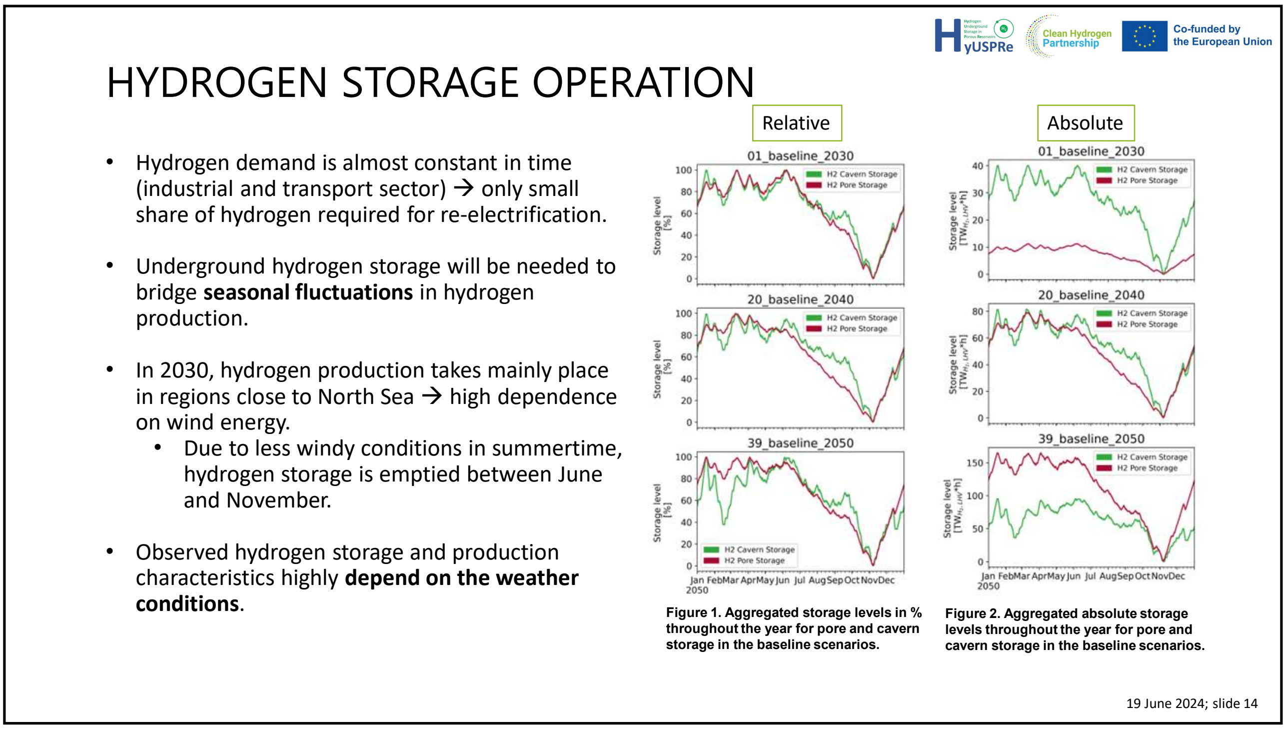
[1] Artelys and frontier economics (2024): Why European Underground Hydrogen Storage Needs Should Be Fulfilled – Final Report.



HYDROGEN INFRASTRUCTURE

Figure 1. Hydrogen transmission (arrows), hydrogen storage capacity (areas) and hydrogen production (filled circles without quantities) in the baseline scenario for 2030.

Figure 2. Hydrogen transmission (arrows), hydrogen storage capacity (areas) and hydrogen production (filled circles without quantities) in the baseline scenario for 2050.



HYDROGEN STORAGE OPERATION

- Hydrogen demand is almost constant in time (industrial and transport sector) → only small share of hydrogen required for re-electrification.
- Underground hydrogen storage will be needed to bridge **seasonal fluctuations** in hydrogen production.
- In 2030, hydrogen production takes mainly place in regions close to North Sea → high dependence on wind energy.
  - Due to less windy conditions in summertime, hydrogen storage is emptied between June and November.
- Observed hydrogen storage and production characteristics highly **depend on the weather conditions**.

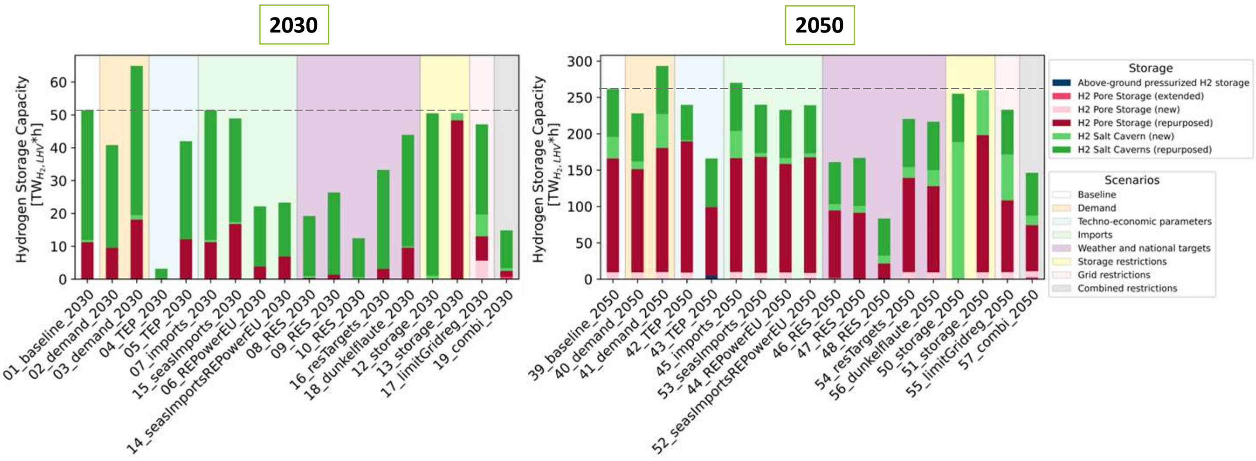
Figure 1. Aggregated storage levels in % throughout the year for pore and cavern storage in the baseline scenarios.

Figure 2. Aggregated absolute storage levels throughout the year for pore and cavern storage in the baseline scenarios.

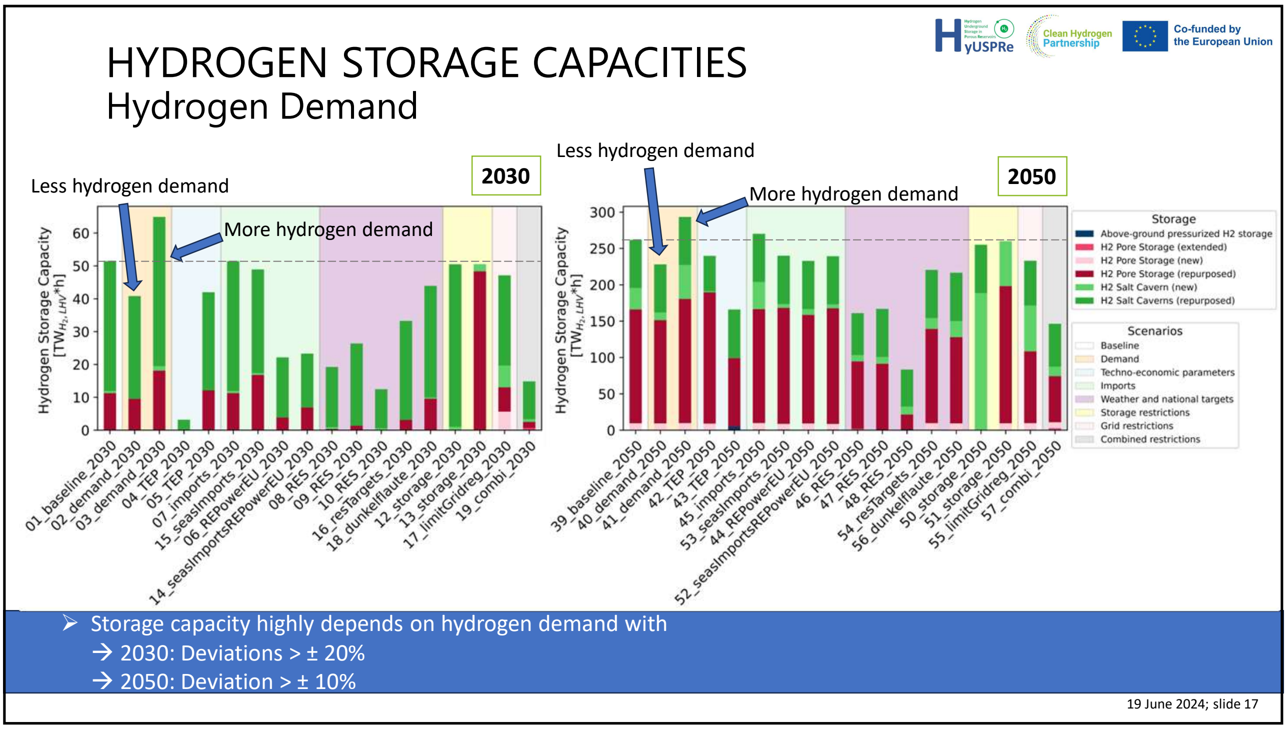
OUTLINE

- Background
- Modeling Approach & Scenario Definitions
- Modeling Results: Baseline Scenarios
- **Modeling Results: Sensitivities**
- Conclusions

HYDROGEN STORAGE CAPACITIES



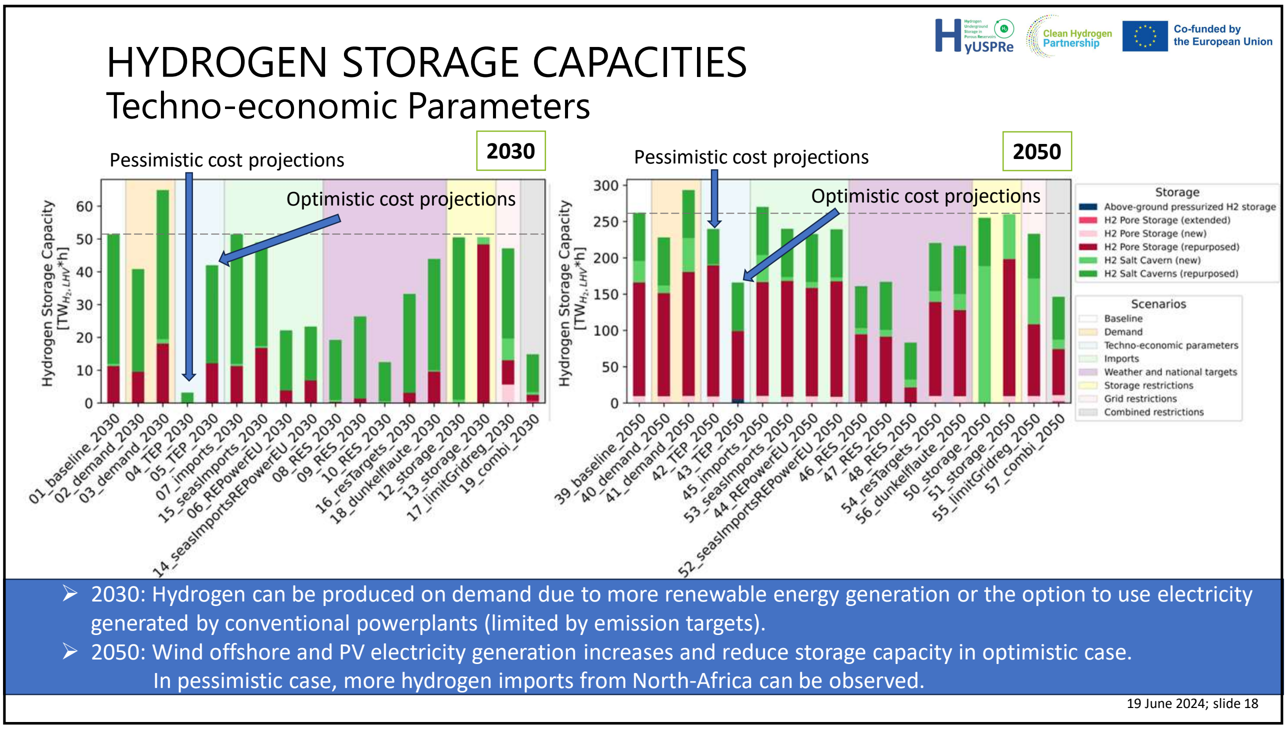
- Underground hydrogen storage is utilized in all modeled scenarios.



HYDROGEN STORAGE CAPACITIES

Hydrogen Demand

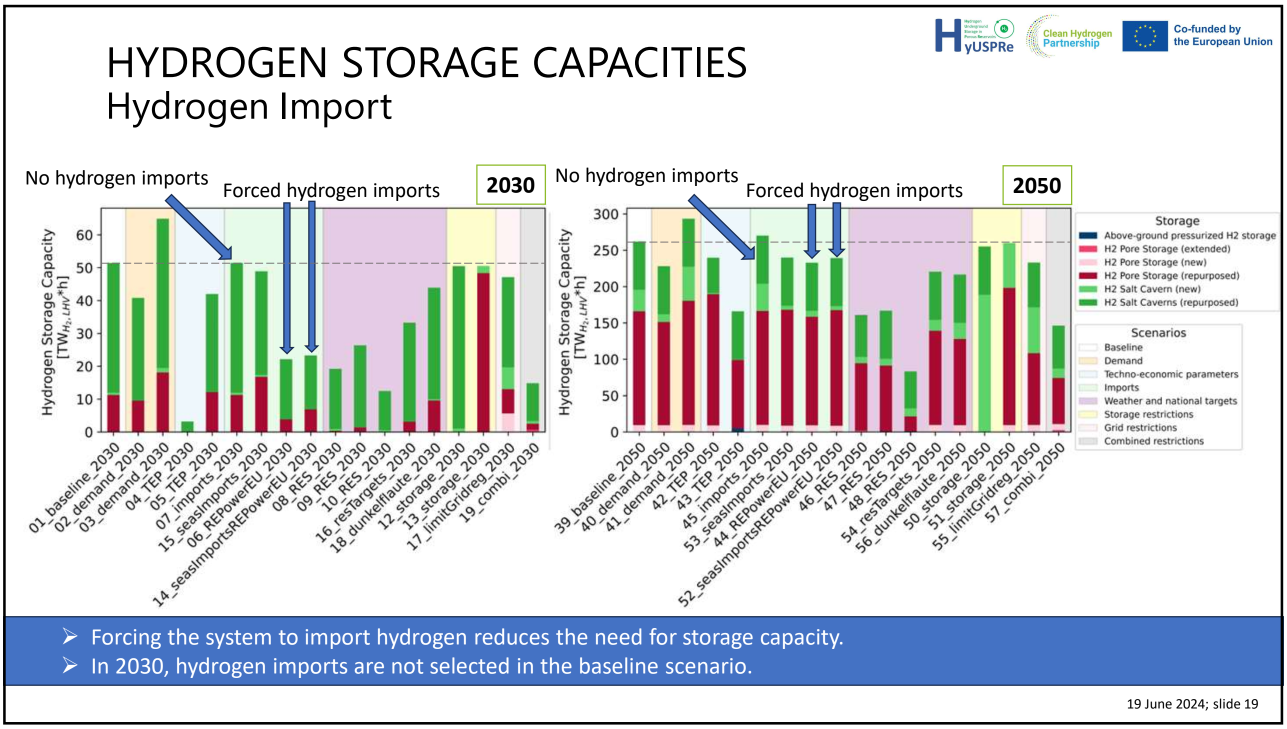
- Storage capacity highly depends on hydrogen demand with
  → 2030: Deviations > ± 20%
  → 2050: Deviation > ± 10%



HYDROGEN STORAGE CAPACITIES

Techno-economic Parameters

- 2030: Hydrogen can be produced on demand due to more renewable energy generation or the option to use electricity generated by conventional powerplants (limited by emission targets).
- 2050: Wind offshore and PV electricity generation increases and reduce storage capacity in optimistic case.
  In pessimistic case, more hydrogen imports from North-Africa can be observed.



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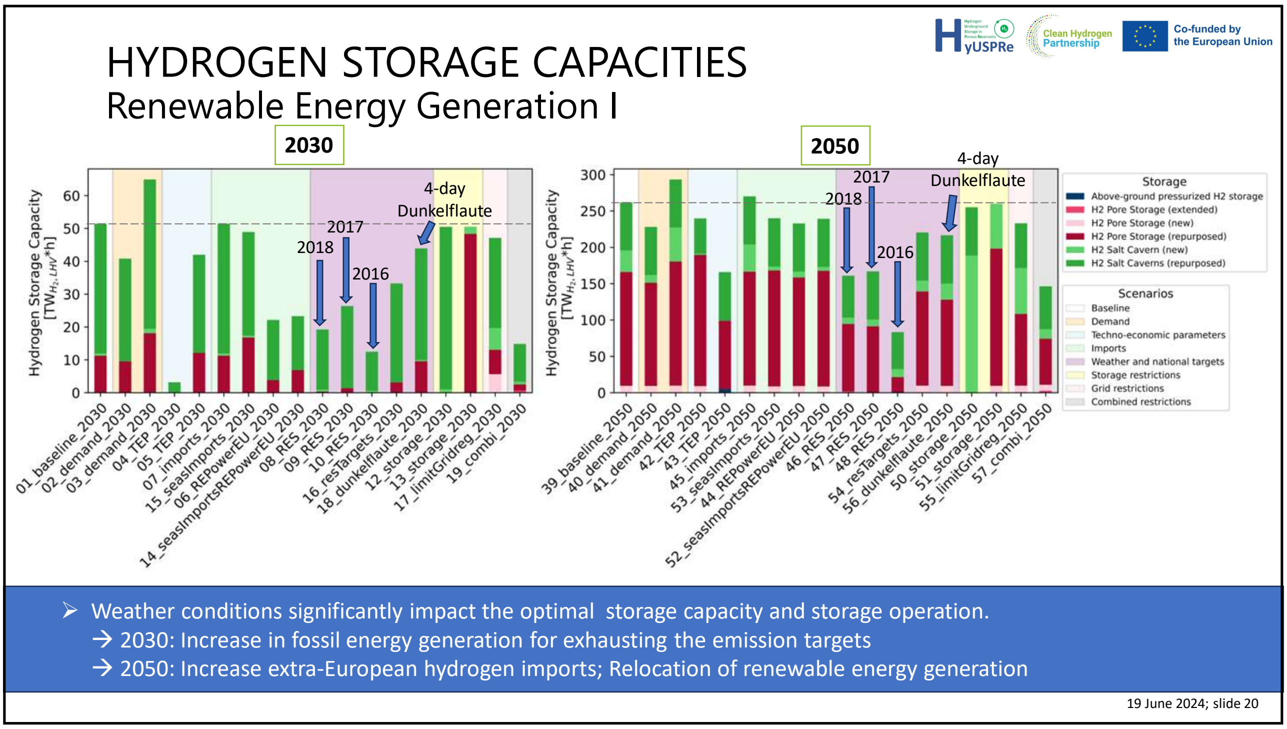
Clean Hydrogen Partnership

HyUSPRe

HYDROGEN STORAGE CAPACITIES

Hydrogen Import

- ➢ Forcing the system to import hydrogen reduces the need for storage capacity.
- ➢ In 2030, hydrogen imports are not selected in the baseline scenario.



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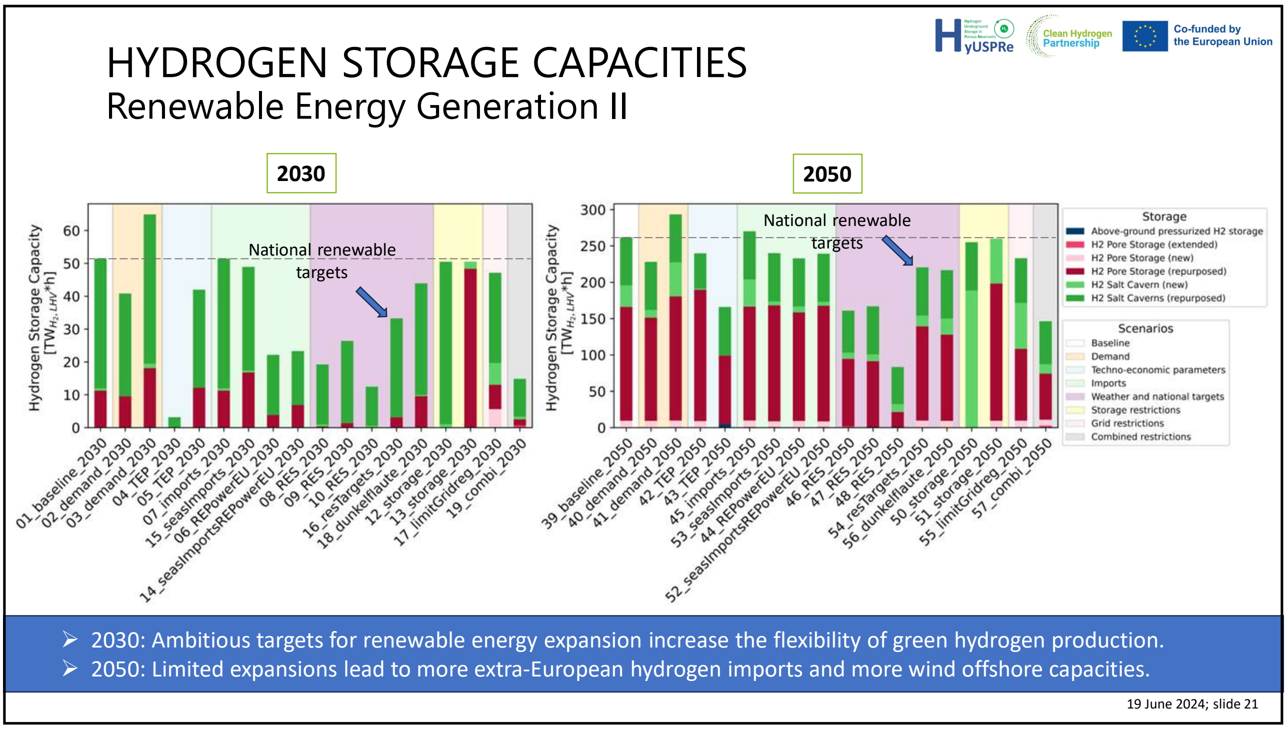
Clean Hydrogen Partnership

HyUSPRe

HYDROGEN STORAGE CAPACITIES

Renewable Energy Generation I

- ➢ Weather conditions significantly impact the optimal storage capacity and storage operation.
  - → 2030: Increase in fossil energy generation for exhausting the emission targets
  - → 2050: Increase extra-European hydrogen imports; Relocation of renewable energy generation



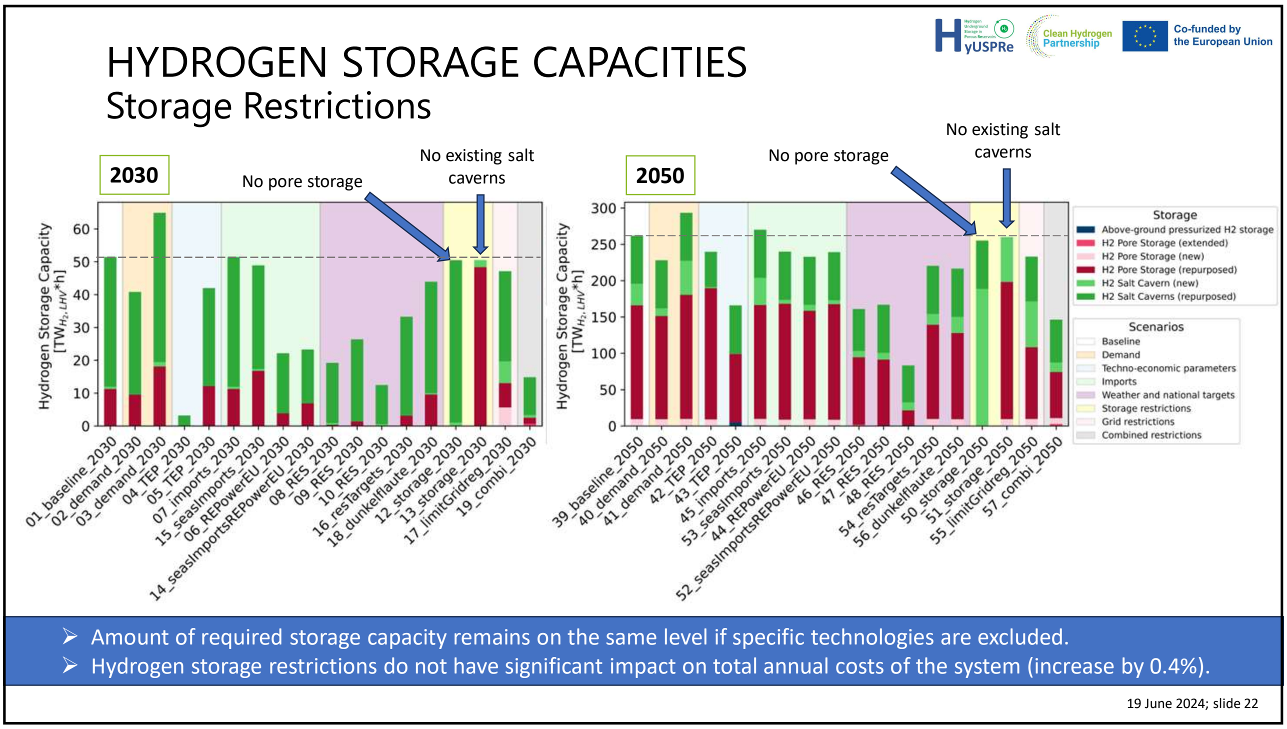
Hydrogen Underground Storage in Porous Reservoirs HyUSPRe · Clean Hydrogen Partnership · Co-funded by the European Union

HYDROGEN STORAGE CAPACITIES

Renewable Energy Generation II

- 2030: Ambitious targets for renewable energy expansion increase the flexibility of green hydrogen production.
- 2050: Limited expansions lead to more extra-European hydrogen imports and more wind offshore capacities.

19 June 2024; slide 21



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HYDROGEN STORAGE CAPACITIES

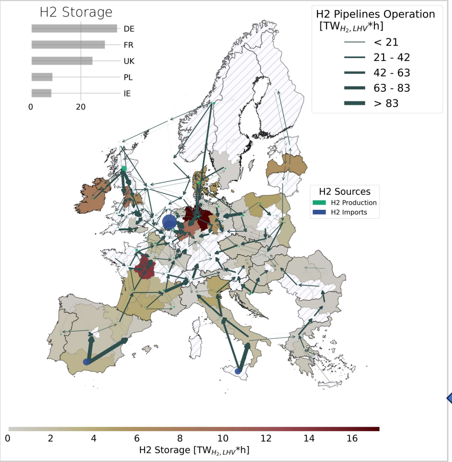
Storage Restrictions

- Amount of required storage capacity remains on the same level if specific technologies are excluded.
- Hydrogen storage restrictions do not have significant impact on total annual costs of the system (increase by 0.4%).

19 June 2024; slide 22

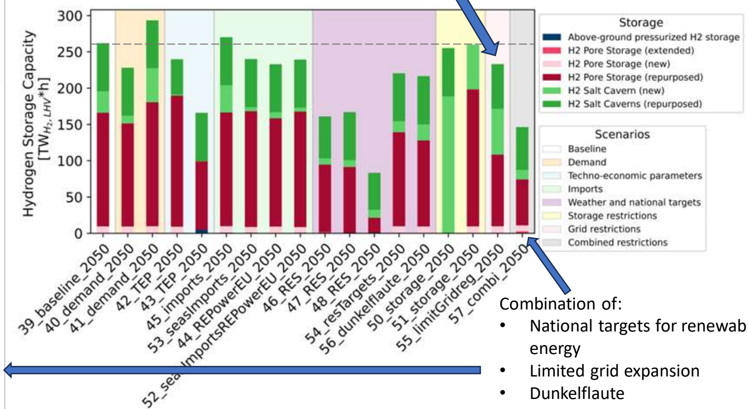
Hydrogen Underground Storage in Porous Reservoirs HyUSPRe | Clean Hydrogen Partnership | Co-funded by the European Union

HYDROGEN STORAGE CAPACITIES
Further Restrictions



2050

Electricity and hydrogen grid expansion is limited



Combination of:

- National targets for renewable energy
- Limited grid expansion
- Dunkelflaute
- Forced seasonal imports (REPowerEU)

- ➢ Limiting grid expansion leads to more decentralized hydrogen production.
- ➢ In combination with forced hydrogen imports, liquid hydrogen imports are selected.

Hydrogen Underground Storage in Porous Reservoirs HyUSPRe | Clean Hydrogen Partnership | Co-funded by the European Union

OUTLINE

Background

Modeling Approach & Scenario Definitions

Modeling Results: Baseline Scenarios

Modeling Results: Sensitivities

Conclusions

CONCLUSIONS

- Optimal underground hydrogen storage capacity is dictated by multifaceted interplay of determinants.
- From a cost perspective, pore storage capacities are not indispensable for the future European energy system
  - ➢ Total annual cost improvements of approximately 0.4%.
  - ➢ However, implementing pore storage capacities enables a more decentralized approach to hydrogen storage across Europe.
- Weather conditions have a strong impact on the resulting optimal storage.
  - ➢ Storage capacity requirements are chiefly dictated by the balance of surplus or deficit residual electricity available for hydrogen production.
  - ➢ Due to changes in weather conditions in exporting extra-European countries hydrogen imports can become more favorable.
- Limiting renewable expansion increases reliance on external hydrogen sources.
- Limiting grid expansion leads to more decentralized hydrogen production.

➢ Underground hydrogen storage will be crucial in the future European energy system due to the increasing prominence of hydrogen in the energy transition.

HYUSPRE
TECHNO-ECONOMIC ASSESSMENT OF EU SCALE HYDROGEN SYSTEM SCENARIOS

THANK YOU FOR LISTENING

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.

This document reflects the views of the author(s) and does not necessarily reflect the views or policy of the European Commission. Whilst efforts have been made to ensure the accuracy and completeness of this document, the HyUSPRe consortium shall not be liable for any errors or omissions, however caused.

Hydrogen storage assessments and implemenation scenarios
[06] What did we learn from the 'sister' project Hystories (*Arnaud Réveillère*, Geostock)

Hystories - What did we learn from the ‘sister’ project Hystories

Arnaud REVEILLERE[1] + Hystories team
1: Geostock, France

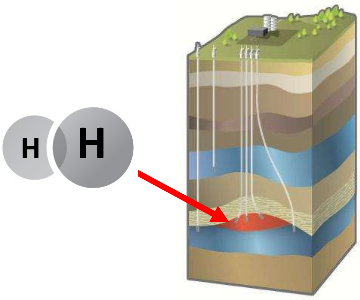
HyUSPRe final conference, 19/06/2024

Acknowledgment

Context of the 2020 Clean Hydrogen Partnership call for proposals and Hystories’ 2021-2023 work

Context

Solution considered in this project



Pure hydrogen storage in porous media had never been done. Technical developments are needed

→ Hystories

Decision makers need insights. Storage demand, environmental/societal impacts studies, case studies are needed

→ Hystories

Project consortium from 17 European countries

hystories
Hydrogen Storage in European Subsurface

Project Partners:

Geostock

MONTAN UNIVERSITÄT

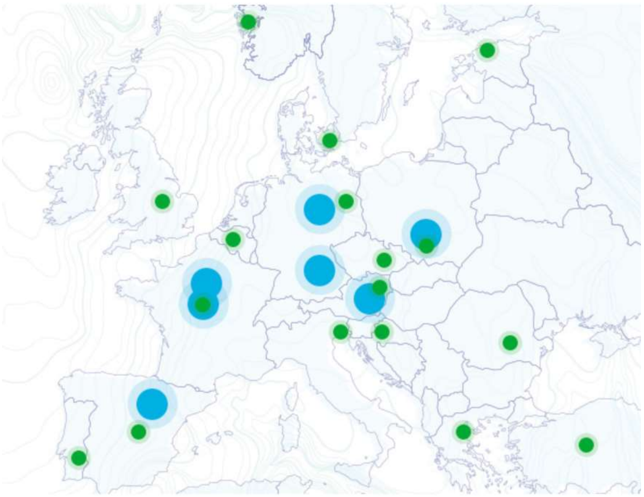
CO2 GeoNet

Fundación para el Desarrollo de las Nuevas Tecnologías del Hidrógeno en Aragón

ludwig bölkow systemtechnik

MicroPro GmbH
Microbiological Laboratories

Mineral and Energy Economy Research Institute
Polish Academy of Sciences



Third Parties:

BGS British Geological Survey, brgm, CERTH, Czech Geological Survey, GeoEcoMar, GiG, NORCE, OGS, TalTech, GFZ, ICT

Advisory Board:

enagas, IGS Ital Gas Storage, FLUXYS, OGE, ontras, RAG Austria AG, uniper, storengy, vallourec, Humbly Grove Energy, VNG, GAZ-SYSTEM, Teréga

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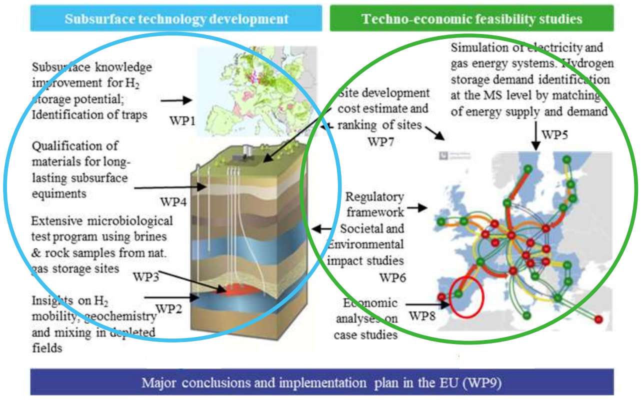
How mature is Underground Hydrogen Storage ?

hystories
Hydrogen Storage in European Subsurface



Subsurface technology development

Techno-economic feasibility studies

Subsurface knowledge improvement for H_2 storage potential; Identification of traps — WP1

Qualification of materials for long-lasting subsurface equiments — WP4

Extensive microbiological test program using brines & rock samples from nat. gas storage sites — WP3

Insights on H_2 mobility, geochemistry and mixing in depleted fields — WP2

Simulation of electricity and gas energy systems. Hydrogen storage demand identification at the MS level by matching of energy supply and demand — WP5

Site development cost estimate and ranking of sites — WP7

Regulatory framework Societal and Environmental impact studies — WP6

Economic analyses on case studies — WP8

Major conclusions and implementation plan in the EU (WP9)

1 – Technical maturity of porous UHS

2- Techno-economic maturity of UHS

3- Implementation plan towards an industrial deployment

4- Hystories tools for planning UHS deployment in Europe

1

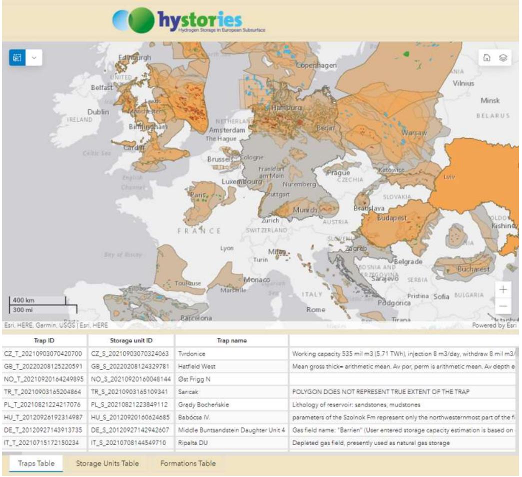
Technical maturity of porous UHS

European Porous trap Geographical Information System and public database

State of the Art

- No hydrogen storage Europe-wide public info database
- European scale CO2Stop, ESTMap databases, not focused on hydrogen
- Usually not coupled with (latest) salt deposit databases

Hystories main developments



Trap ID	Storage unit ID	Trap name	
CZ_T_20210903070420700	CZ_S_20210903070324063	Tvrdonice	Working capacity 535 mil m3 (5,71 TWh), injection 8 m3/day, withdraw 8 mil m3/
GB_T_20220208125220591	GB_S_20220208124329781	Hatfield West	Mean gross thick= arithmetic mean. Av por, perm is arithmetic mean. Av depth e
NO_T_20210920164249895	NO_S_20210920160048144	Øst Frigg N	
TR_T_20210903165204864	TR_S_20210903165109341	Sarıcak	POLYGON DOES NOT REPRESENT TRUE EXTENT OF THE TRAP
PL_T_20210821224217076	PL_S_20210821223849112	Grędy Bocheńskie	Lithology of reservoir: sandstones, mudstones
HU_T_20120926192314987	HU_S_20120920160624685	Babócsa IV.	parameters of the Szolnok Fm represent only the northwesternmost part of the f
DE_T_20120927143913735	DE_S_20120927142942607	Middle Buntsandstein Daughter Unit 4	Gas field name: "Barrien" (User entered storage capacity estimation is based on
IT_T_20210715172150234	IT_S_20210708144549710	Ripalta DU	Depleted gas field, presently used as natural gas storage

https://bgs.maps.arcgis.com/apps/dashboards/630ec7b3cbd54e39b4111e397315ae99

Gaps for UHS deployment

- Uneven data completeness among countries
- Private data not always included for O&G fields
- New data collection required esp. for aquifers
- Lined rock caverns options are not included

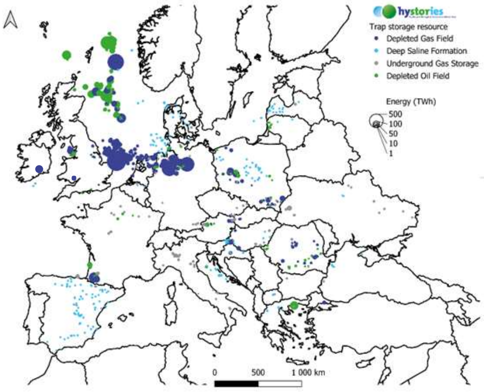
→Call for enhancing data collection at European scale and improving the db

Porous media capacity estimations

State of the Art

- Porous storage capacity estimations based on the sole conversion of existing natural gas underground storages
  - GIE/Guidehouse (2021)
  - HyUSPRe (2022)
- History of overestimations in CCS and in shale gas ressources
- Technical capacity estimation for salt (Caglayan et al. 2020)

Hystories main developments



From www.hystories.eu . Derived from D2.2-0 - 3D Multi-realization simulations for fluid flow and mixing issues

Gaps for UHS deployment

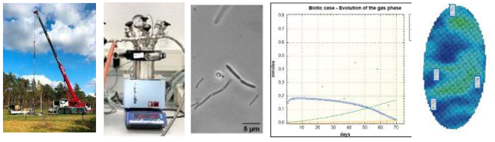
- Storage performance for porous UHS needs industrial reference (mixing, fingering…)
  - → Call for Field scale porous UHS

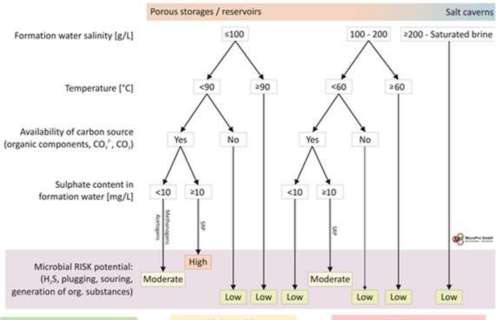
Microbiological risk assessment

State of the Art

- Hydrogen known to be a very strong reductor. In abiotic conditions reactions should not happen under storage temperatures (below 200°C), due to the kinetics
- Biotic reactivity known to happen from Town gas and pilots. Characterized at laboratory scale (e.g. Thaysen et al., 2021)

Hystories main developments





From D3.2

Gaps for UHS deployment

- Highly site-specific risk
  - → Call for enlarging the scale of the sampling, characterization and testing to strengthen risk mapping
- Risk assessment mostly derived from lab-studies. Need for model dvpt and validation based on at scale porous UHS observations
  - → Call for pilots over 10+ years

Material and corrosion

State of the Art

- Wells are a UHS' main man-builtt structure
  - Standards exist, developped by and for the O&G industry (API)
- Hydrogen raises new questions (embrittlement…)
  - Standards exist for H2 in surface applications
- There is no applicable standard for H_2 wells !

Hystories main developments

Material	Damage	Application with H_2S based on ISO 15156	Applicability in H_2 environment
20MnV5	no damage	Not specified	well applicable
welded J55 welded J55 pre-corroded welded J55 with notch	no damage no damage no damage	Acceptable for H_2S application for all temperatures	well applicable
K55 K55 pre-corroded K55 with notch	no damage no damage some localized damage	Acceptable for H_2S application for all temperatures	well applicable when localized corrosion is not an issue
welded K55	no damage	Acceptable for H_2S application if hardness ≤ 22 HRC	well applicable
	deep localized		

Vallourec Qualifies Materials for a Wide Range of Hydrogen Applications

Hydrogen is set to play a key role in the energy transition acting as a low-emission energy carrier for various applications.

These qualification results are in line with those obtained by the HystorIES project of which Vallourec is part of. Vallourec's L80 and K55 grades were successfully tested using different methodologies in a more demanding corrosive environment in porous media. Read HystorIES's material qualification reports here. The tests also fall within

From D4.6-0 Summary report on all investigated steels and https://www.vallourec.com/en/all-news/group-2022-hydrogen-materials

Gaps for UHS deployment

- Increasing number of references but still no standard for well casings
  → Call for standardisation
- Standards are also needed for the well equipments
  → Call for involving equipement Manufacturers in a Pre-normative approach
- Wells aren't all new.
  → Call for a re-qualification procedure

2

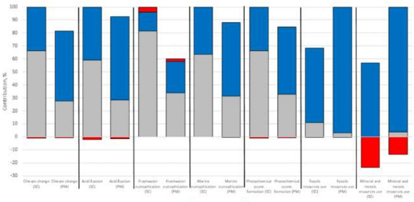
Techno-economic findings and insights

Permitting readiness, Environmental footprint and Public perception

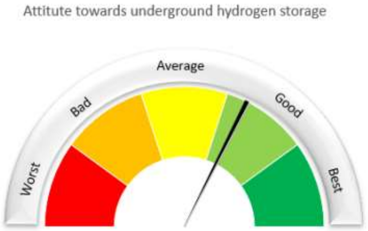
State of the Art

- Hardly a coherent view on permitting readiness at European scale
- Lack of reference data for Environmental footprint of an UHS site over its life cycle
- Attention to the public perception when developing UHS. Experience of CCS vs. natural gas storages

Hystories main developments



From D6.3 - Results for Environmental-LCA



From D6.4 - Social impact of the underground H2 storage

Gaps for UHS deployment

→ Call for « Administrative experiment » through pilots

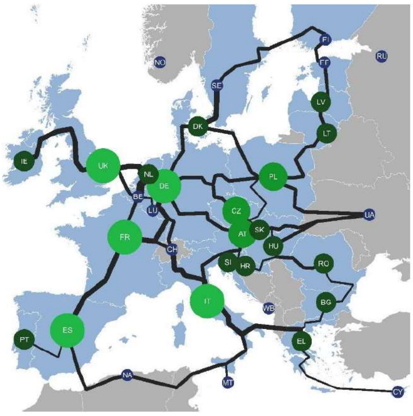
→ Call for actions promoting societal information and actions helping embeddedness for UHS

Optimal UHS for Europe

State of the Art

- « Hydrogen storage is needed to bridge the mismatch between green energy production and demand »
- Analytical analyses of storage drivers and of offtakers needs
- Scenario-based and asumption-based projections of future hydrogen storage demand

Hystories main developments



From D5.5-2 - Major results of techno-economic assessment

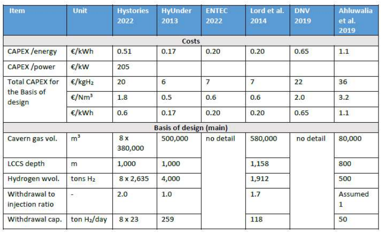
Gaps for UHS deployment

- Will a network develop as per Economic optimum ? How to capture energy independance objectives (REPower EU) ?
  → Call for comprehensive analysis, incl. « societal benefits » externalities
- Capture of regional hydrogen valleys
  → Call for fine spatial resolution energy modelling

Cost estimation

State of the Art

- Public sources of UHS cost gave capacity-based costs (€/MWh), never deliverability-based (€/MW)



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

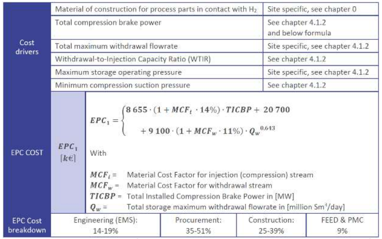
Hydrogen TCP-Task 42, 2023

- Unclear boundary limits

Hystories main developments

Cost model :

- H2-specific, for salt & porous
- Based on a well defined design, with clear boundaries
- Parametric → can be site- and cycle-specific



Cost drivers	Material of construction for process parts in contact with H₂	Site specific, see chapter 0
	Total compression brake power	See chapter 4.1.2 and below formula
	Total maximum withdrawal flowrate	Site specific, see chapter 4.1.2
	Withdrawal-to-Injection Capacity Ratio (WTIR)	See chapter 4.1.2
	Maximum storage operating pressure	Site specific, see chapter 4.1.2
	Minimum compression suction pressure	See chapter 4.1.2
EPC COST	EPC_1 $[k€]$	$EPC_1 = \begin{cases} 8\,655 \cdot (1 + MCF_i \cdot 14\%) \cdot TICBP + 20\,700 \\ + 9\,100 \cdot (1 + MCF_w \cdot 11\%) \cdot {Q_w}^{0{,}643} \end{cases}$ With MCF_i = Material Cost Factor for injection (compression) stream MCF_w = Material Cost Factor for withdrawal stream $TICBP$ = Total Installed Compression Brake Power in [MW] Q_w = Total storage maximum withdrawal flowrate in [million Sm³/day]
EPC Cost breakdown	Engineering (EMS): 14-19% Procurement: 35-51% Construction: 25-39% FEED & PMC 9%	

From D7.2-1: Life Cycle Cost Assessment of an underground storage site

Gaps for UHS deployment

- No recent UHS to serve as a reference
- Gas treatment cost needs particular focus. Strong impact on porous deployment.

→ Call for sharing the data from industrial pilots and projects

3

Implementation plan towards an industrial deployment ?

High similarities between Natural Gas and Hydrogen storage. But some differences…

- Difference in physical and chemical properties
  - Higher reactivity that is catalized by anaerobic microorganisms
  - Hydrogen embrittlement
  - lower viscosity (fingering), energy density
- Deployment spatial and time-frame
  - A major infrastructure industry has to develop in only a few decades
  - European deployment now, not national ones anymore
- Established industry vs. developping one
  - Storage drivers (supply and offtakers) are different
  - Hypothetical vs. established storage needs and cycles
  - Conceptual vs. established business cases
- Development of infrastructures in the 2030s-2050s
  - Attention for Environmental footprint, Societal embeddedness are key

- Hydrogen Storage in salt caverns (50 years experience) is seen as mature. However, technical development is not a continuous process (cf. SMRI report Buzogany et al. 2023), and « maturity » is not only technical
- No obvious show stopper for Hydrogen storage in depleted fields or aquifers. However, the purity upon withdrawal, gas treatment costs and H2 grid specifications may impact this deployment

---

…call for new data gathering, Demonstration, Normalization and Business/Regulatory frame development actions

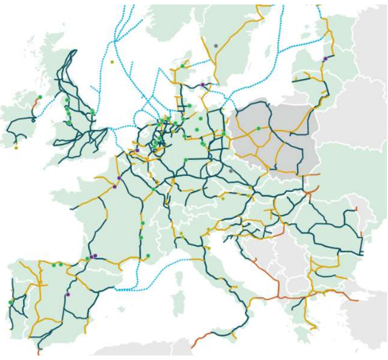
- Call for geological data collection
  - at European scale, improving the public database on depleted fields and aquifers (data proprietary access and/or acquisition)
  - Inclusion of salt and lined rock caverns
- Call for publication of insights
  - comprehensive energy modelling incl. « societal benefits » externalities, fine grid to capture small scale hydrogen valleys early deployment opportunities
  - comparison of UHS Environmental footprint with alternative technical options enabling Net-Zero by 2050
- Call for actions promoting embeddedness for UHS
  - Sharing of information, notably on pilots
  - Involvement of stakeholders/public
- Call for pilots
  - Large scale, to enable validating modeled reservoir flow behavior/mixing, and reactive transport models
  - Diverse and numerous, to enlarge the and strengthen the microbial risk mapping, and to conduct « Administrative experiments » in many countries
  - Over 10+ years to calibrate microbial reactivity models
- Call for standardisation
  - Standardisation of steel grades for H2 service
  - Pre-normative approach for well equipment
  - Procedure for re-qualification of existing wells
  - Setting of future H2 grid specifications
- Call for business frames and regulation
  - Setting of business options to support first projects
  - Investigation of legal frames especially for strategic storage purpose (cf. oil storage experience)

4

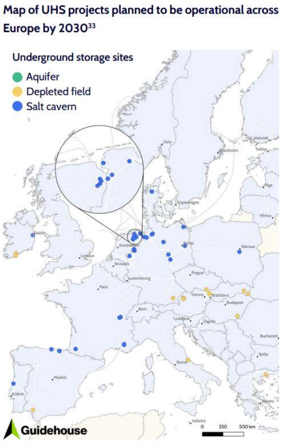
Hystories insights into UHS industrial deployment

There is a clear and public vision from the European gas industry on UHS deployment

Natural gas TSOs (European Hydrogen Backbone) and SSOs (H2eart for Europe) have published their vision



https://ehb.eu

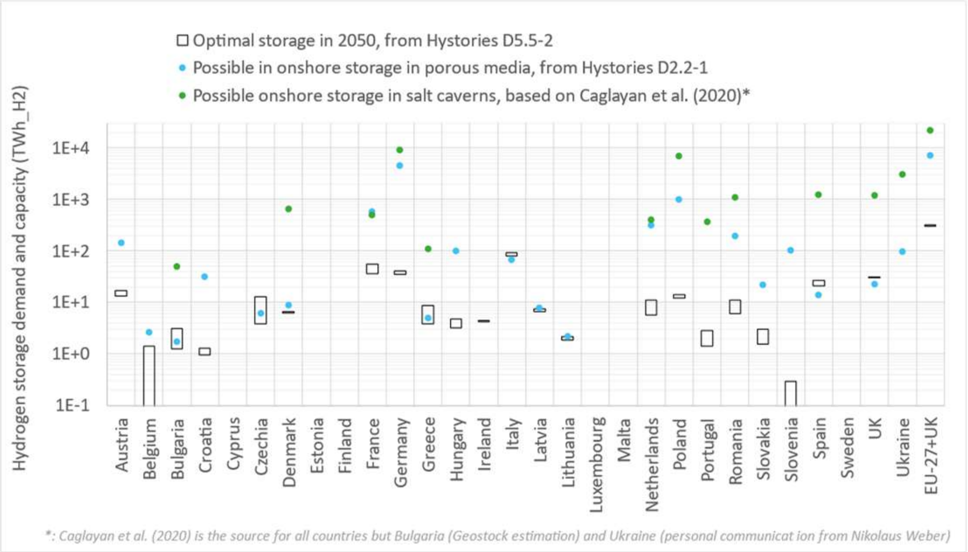


Map of UHS projects planned to be operational across Europe by 2030[33]

https://h2eart.eu/

Can Hystories help ?

European-scale (high level) technical capacity and vs. demand



**: Caglayan et al. (2020) is the source for all countries but Bulgaria (Geostock estimation) and Ukraine (personal communicat ion from Nikolaus Weber)*

- For nearly all countries, Technical capacity is much higher than demand
- Only considering onshore options
- Both in salt and in porous reservoirs

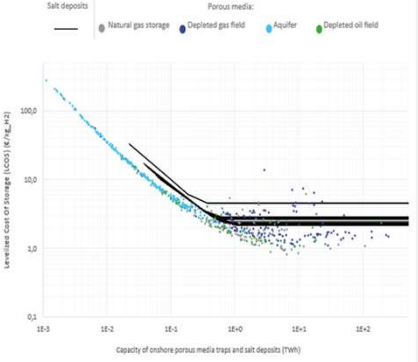
From D7.3-1 – Ranking and selection of geological stores

Enabling homogeneous ranking of 800+ porous media traps, 18 bedded salt deposits and salt domes

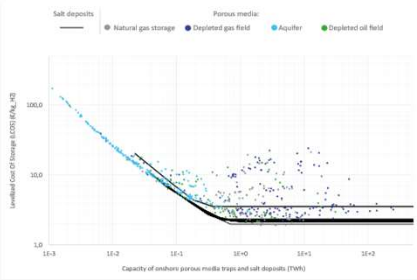
UHS cost is site-specific and cycle-specific

→ High-level, but European-scale estimation of the costs and technical suitability

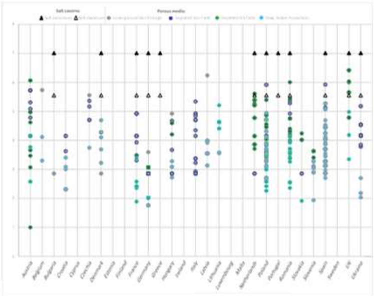
LCOS for seasonal storage



LCOS for fast storage

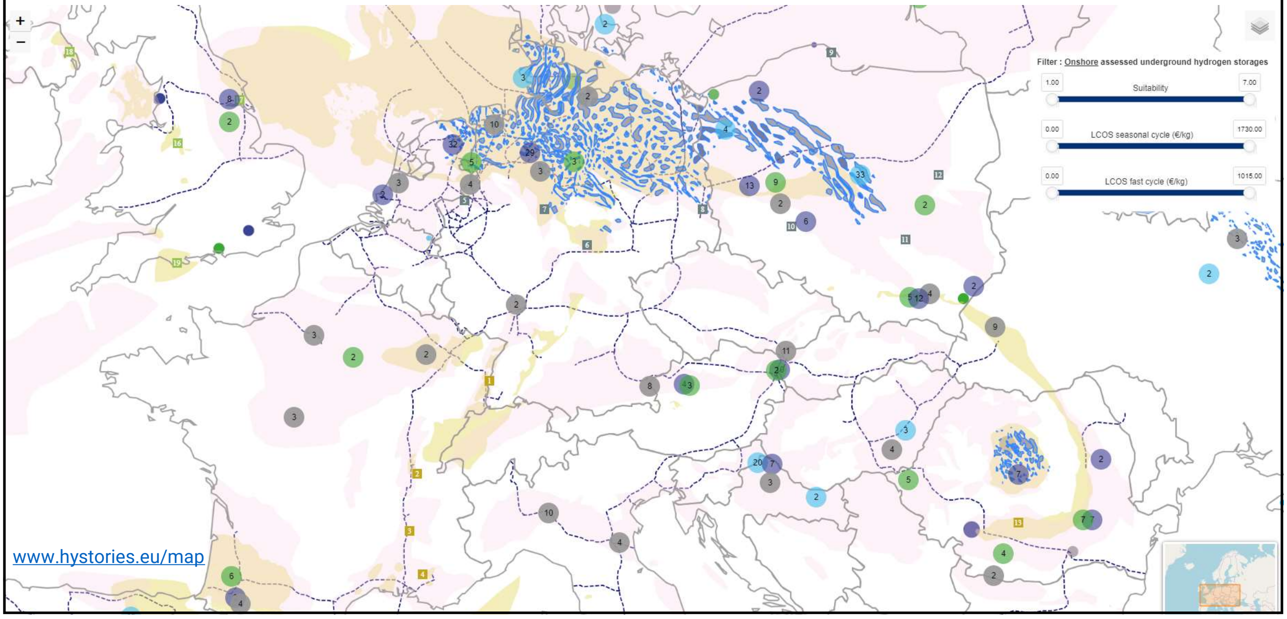


Suitability mark



From D7.3-1 – Ranking and selection of geological stores

Ranking and selection: Opportunities are also local. How to account for it ?


Filter : Onshore assessed underground hydrogen storages

Suitability: 1.00 – 7.00

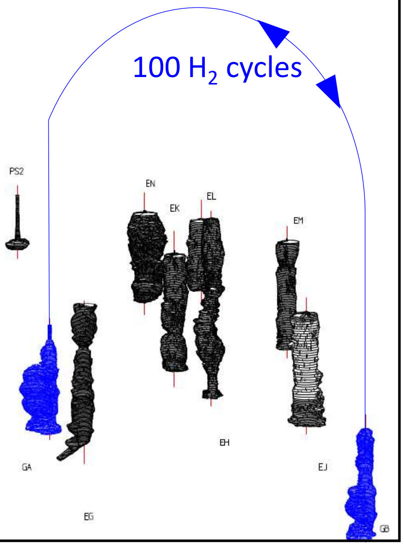
LCOS seasonal cycle (€/kg): 0.00 – 1730.00

LCOS fast cycle (€/kg): 0.00 – 1015.00

www.hystories.eu/map

Stepping up : FrHyGe: Full qualification in France of large-scale Hydrogen underground storage and replication from Germany to all European countries

- Team
  storengy, Géométhane, Geostock, IFP Energies nouvelles, ARMINES, GRTgaz, République Française, INERIS, Axens, Artelys, ECO-MED, MINES PARIS, ESK, enagas, Capenergies
- 2024 – 2029 project co-funded by the UE Clean Hydrogen Partnership (CHP). The project is supported by the CHP and its members.
- Main objectives are:
  - the demonstration of Hydrogen Storage in 2 salt caverns (100 tonnes, up to 1 t/h)
  - technology developments
  - Deployement and replication of both at industrial scale throughout Europe



Hystories project consortium

Geostock

ludwig bölkow systemtechnik

MONTAN UNIVERSITÄT

CO2 GeoNet

MicroPro GmbH
Microbiological Laboratories

FUNDACIÓN PARA EL DESARROLLO DE LAS NUEVAS TECNOLOGÍAS DEL HIDRÓGENO EN ARAGÓN

Mineral and Energy Economy Research Institute
Polish Academy of Sciences

Acknowledgment

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 101007176. This Joint Undertaking receives support from the European Union’s Horizon 2020 Research and Innovation program, Hydrogen Europe and Hydrogen Europe Research.

The Project is co-funded by European Union

Clean Hydrogen Partnership

References used in this presentation

hystories
Hydrogen Storage in European Subsurface

All Dx.y references refer to a Hystories report publicly available on www.hystories.eu

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GIE, 2021. Picturing the value of underground gas storage to the European hydrogen system. Supported by Guidehouse. J. Cihalr, D. Mavins, K. v.d. Leun. June 2021

Caglayan, D. G., Weber, N., Heinrichs, H. U., Linßen, J., Robinius, M., Kukla, P. A., Stolten, D., 2020. Technical potential of salt caverns for hydrogen storage in Europe. International Journal of Hydrogen Energy, 45(11), 6793-6805

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Thaysen, E. M., McMahon, S., Strobel, G. J., Butler, I. B., Ngwenya, B. T., Heinemann, N., & Edlmann, K. (2021). Estimating microbial growth and hydrogen consumption in hydrogen storage in porous media. Renewable and Sustainable Energy Reviews, 151, 111481.

Questions ?

Contact: arnaud.reveillere@geostock.fr

What did you learn from the ‘sister’ project Hystories ?

Impact of cyclic hydrogen storage on the reservoir and well system

[07] Durability and integrity of rock and well materials under hydrogen storage conditions (Jan ter Heege, TNO)

HYUSPRE – PROJECT FINAL MEETING
19 JUNE 2024 | UTRECHT

WP5 – DURABILITY AND INTEGRITY OF ROCK AND WELL MATERIALS UNDER HYDROGEN STORAGE CONDITIONS

JAN TER HEEGE
VINCENT SOUSTELLE

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.

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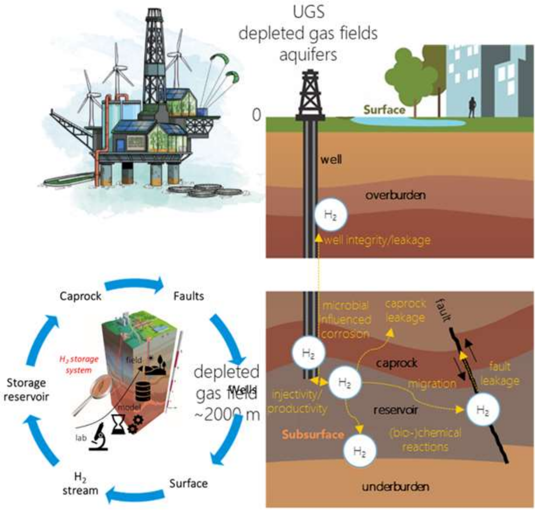
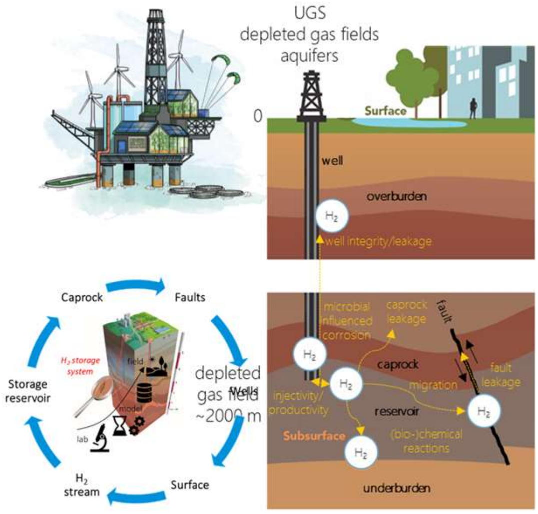
Scope & activities WP5



Durability & integrity of well and rock materials:

- Review, analyze, compile and extend relevant **experimental data of well materials**
- Review, analyze, compile and extend relevant **experimental data of reservoir and sealing rock formations**
- **Experiments on scaled-down well systems** with casing-cement-rock interfaces to evaluate long-term integrity
- Evaluate effects of **microbial-influenced corrosion** (MIC) at high H2 partial pressure conditions
- Assess implications for **hydrogen containment, reservoir injectivity/productivity, hydrogen quality**
- Best practices for mitigation of **loss of durability, integrity & efficiency of H_2 storage system**

Scope & activities WP5- Focus of this presentation



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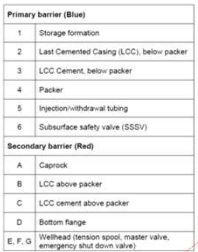
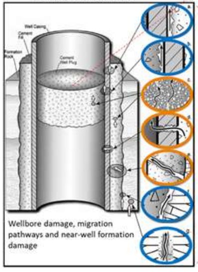
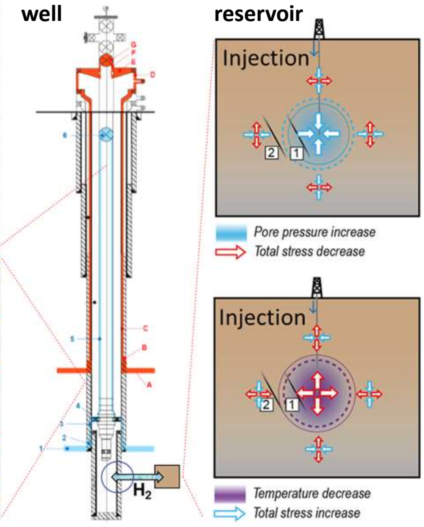
Cyclic injection & withdrawal of hydrogen may impact well systems by interaction of stress changes in reservoir & well



Primary barrier (Blue)	
1	Storage formation
2	Last Cemented Casing (LCC), below packer
3	LCC Cement, below packer
4	Packer
5	Injection/withdrawal tubing
6	Subsurface safety valve (SSSV)
Secondary barrier (Red)	
A	Caprock
B	LCC above packer
C	LCC cement above packer
D	Bottom flange
E, F, G	Wellhead (tension spool, master valve, emergency shut down valve)





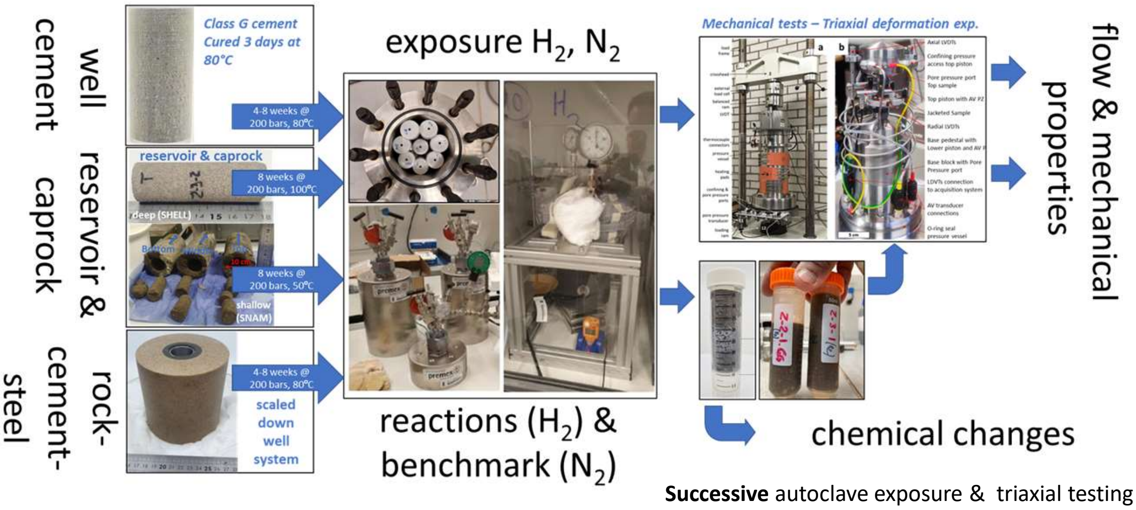
Gasda et al. 2004; Buijze et al. 2018; BVEG 2021

- **Reservoir focus**: Stress changes by cyclic pressure and temperature changes in the reservoir (direct pressure, thermo- & poro-elastic effects) (reservoir focus)
- **Well focus**: Cyclic pressure and temperature changes in the well (affecting well stresses)
- **Material focus**: Reactions between hydrogen and rock/well materials affecting material & interface properties

May lead to:

- Degradation of well materials well integrity issues & leakage along wells
- Near well formation damage reservoir injectivity & productivity losses

Comparison of flow & mechanical properties for well cement and rock materials exposed to N_2 and H_2



well cement

reservoir & caprock

rock-cement-steel

exposure H_2, N_2

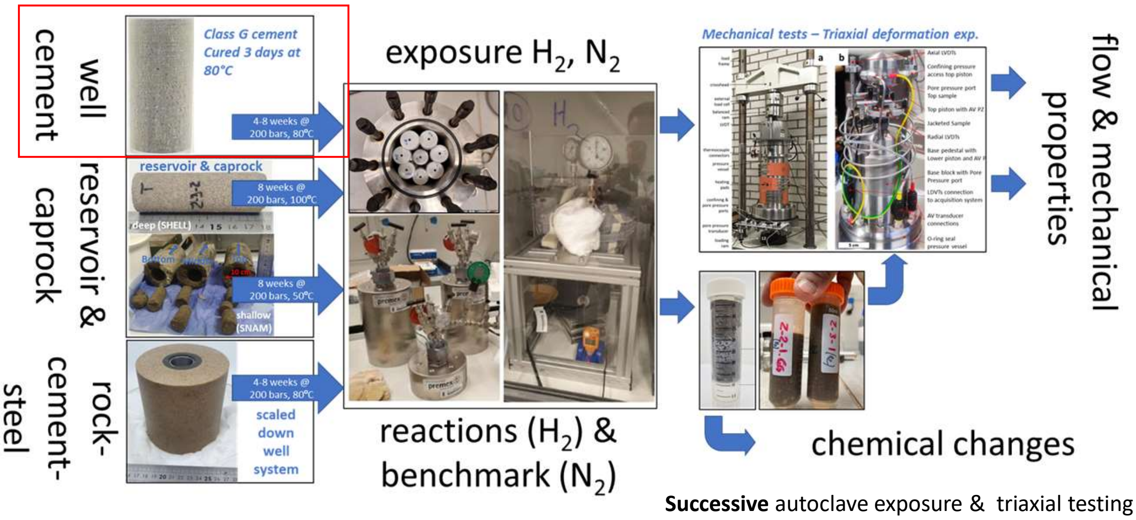
reactions (H_2) & benchmark (N_2)

flow & mechanical properties

chemical changes

Successive autoclave exposure & triaxial testing

Comparison of flow & mechanical properties for well cement and rock materials exposed to N_2 and H_2



well cement

reservoir & caprock

rock-cement-steel

exposure H_2, N_2

reactions (H_2) & benchmark (N_2)

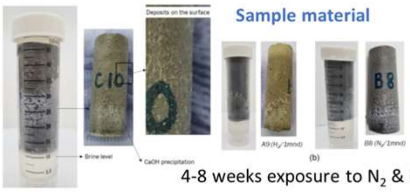
flow & mechanical properties

chemical changes

Successive autoclave exposure & triaxial testing

Limited effects of H_2 exposure or cyclic loading on mechanical properties of well cement

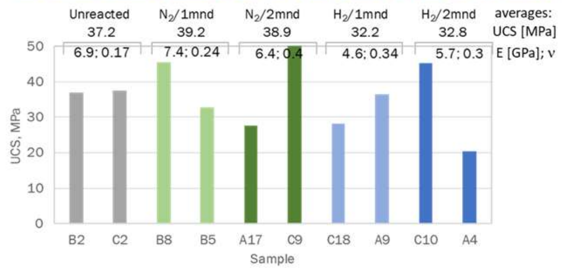
Sample material



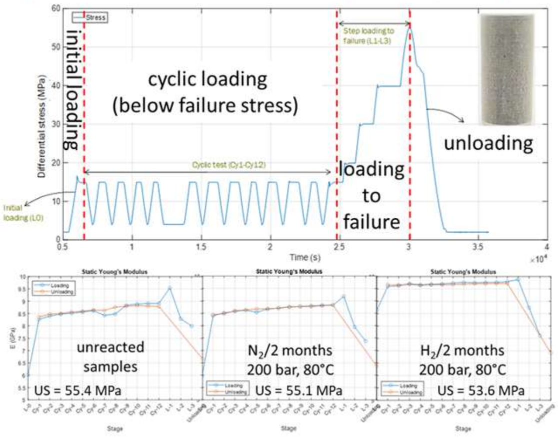
class G cement cured 3 days at 80°C

4-8 weeks exposure to N_2 & H_2 at 20 MPa, 80°C

Unconfined compressive strength (UCS) tests (room temperature)

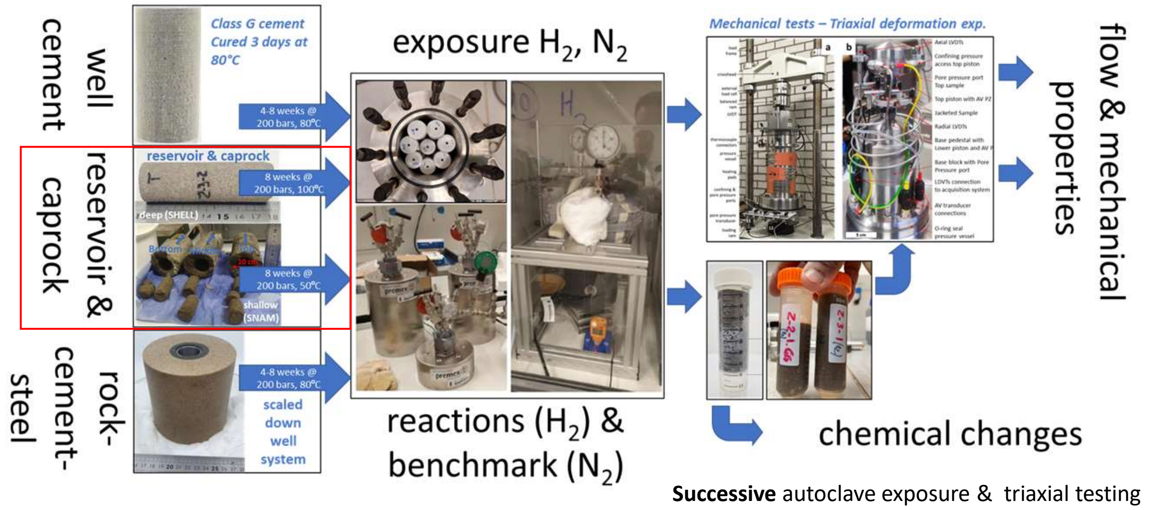


Cyclic differential stress in confined tests (room temperature)



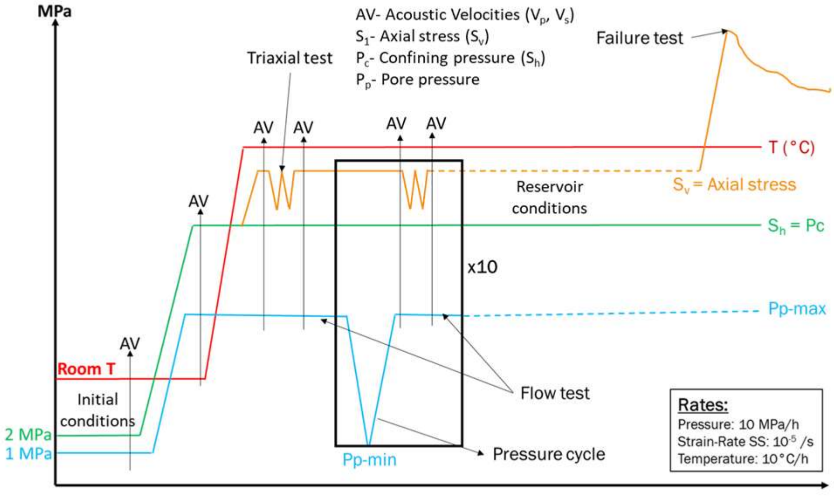
Corina et al. 2023- HyUSPRe D5.2

Comparison of flow & mechanical properties for well cement and rock materials exposed to N_2 and H_2

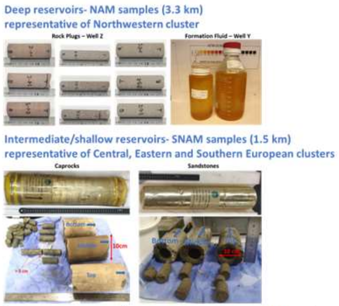


Successive autoclave exposure & triaxial testing

Effects of H_2 exposure and cyclic loading on mechanical properties of sandstone- see poster *Vincent Soustelle*



Rates:
Pressure: 10 MPa/h
Strain-Rate SS: 10^{-5} /s
Temperature: 10°C/h



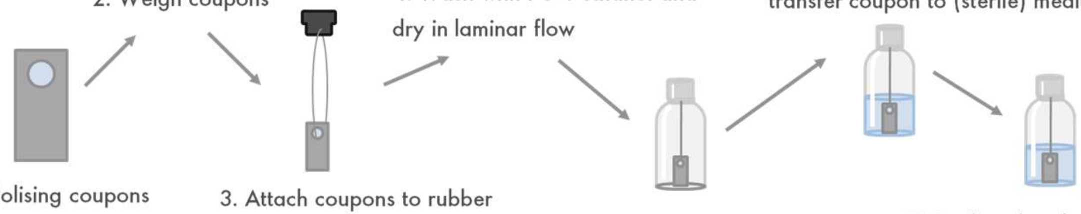
Deep reservoirs- NAM samples (3.3 km) representative of Northwestern cluster

Intermediate/shallow reservoirs- SNAM samples (1.5 km) representative of Central, Eastern and Southern European clusters

	NAM	SNAM
Temp. [°C]	115	50
$P_{initial}$ [MPa]	39.3	18.31
$P_{depleted}$ [MPa]	18	7
S_v [MPa]	71.5	33
S_H [MPa]	55.27	-
S_h [MPa]	52.63	31

Soustelle et al. 2023- HyUSPRe D5.3

Microbial influenced corrosion (MIC) and impacts of high partial pressure of H_2- see report *James Dykstra et al.*



1. Polising coupons to 600 grit

2. Weigh coupons

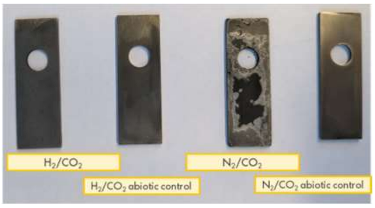
3. Attach coupons to rubber stopper with nylon thread

4. Wash with 70% ethanol and dry in laminar flow

5. Transfer to (sterile) N_2-filled bottle

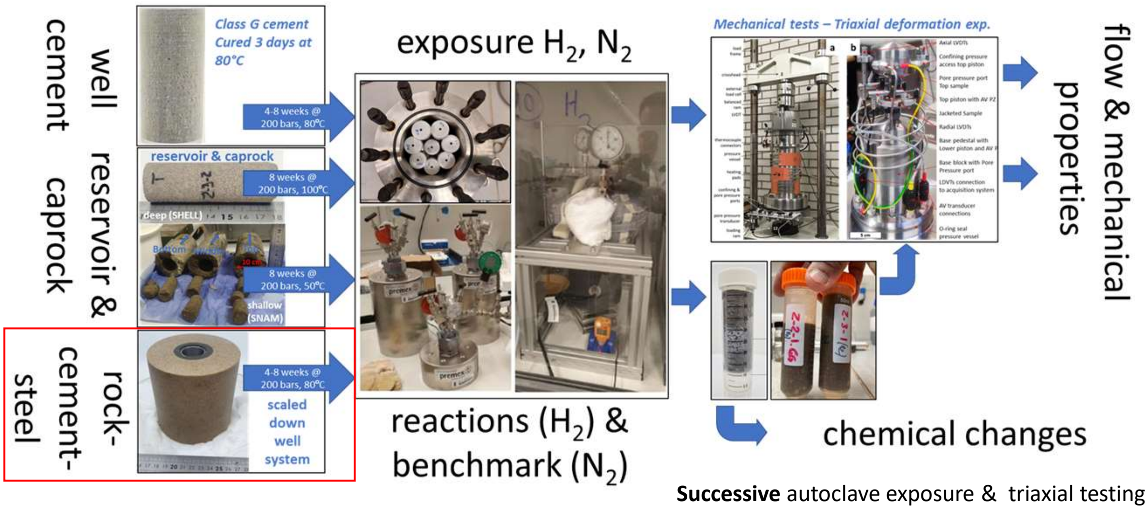
6. Transfer coupon bottle to glovebox and transfer coupon to (sterile) medium bottle

7. Replace headspace with desired gas, inoculate and start experiment



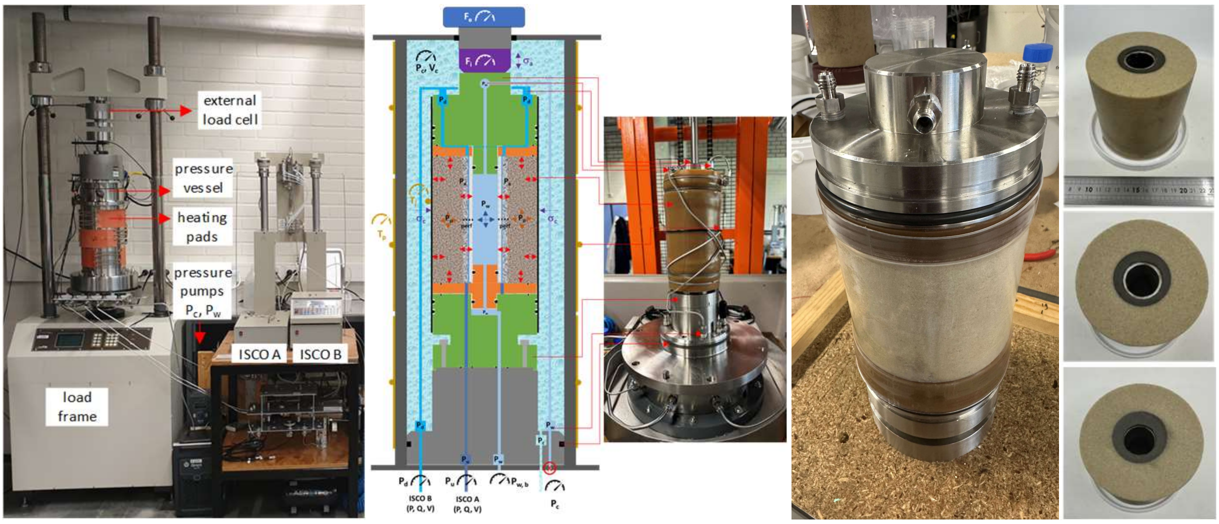
Dykstra et al. 2024- HyUSPRe D5.5

Comparison of flow & mechanical properties for well cement and rock materials exposed to N_2 and H_2

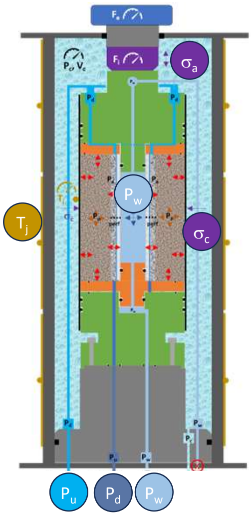


Successive autoclave exposure & triaxial testing

A scaled down well system to test interaction of casing-cement-rock (interfaces) during well pressure cycling



A scaled down well system to test interaction of casing-cement-rock during well pressure cycling



applied conditions

- σ_a axial stress (equivalent to vertical stress S_v ; range ~22-55 MPa, eq. 1.0-2.5 km)
- σ_c confining stress (equivalent to horizontal stress S_h ; range ~16-40 MPa, eq. 1.0-2.5 km)
- P_w well pressure (pressure in steel casing that is cycled; cycles 5-1-5, 10-5-10, 25-5-25 MPa)
- T_j temperature (range 20-75°C, eq. 0.5-2.5 km)

pressure response

- P_u sandstone pore pressure (upstream- bottom sample)
- P_d sandstone pore pressure (downstream- top sample)

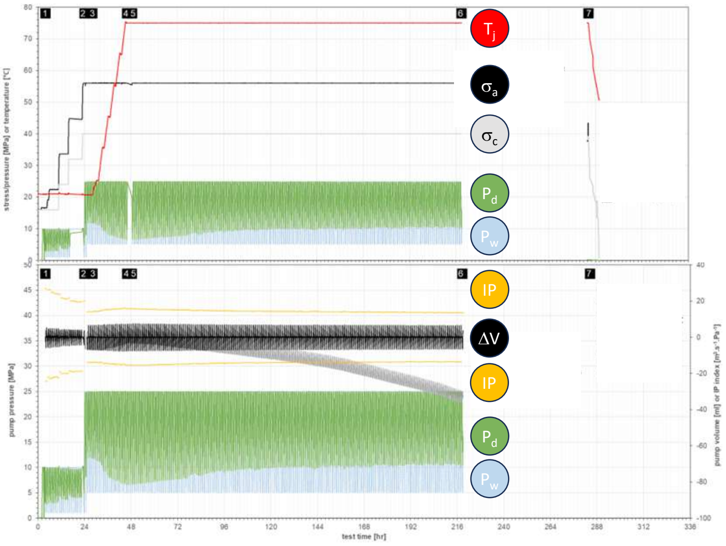
materials

- ▨ sandstone (Bentheim-type)
- ▨ well cement (class G)
- ☐ stainless steel casing
- ▨ confining oil (silicone oil)

setup

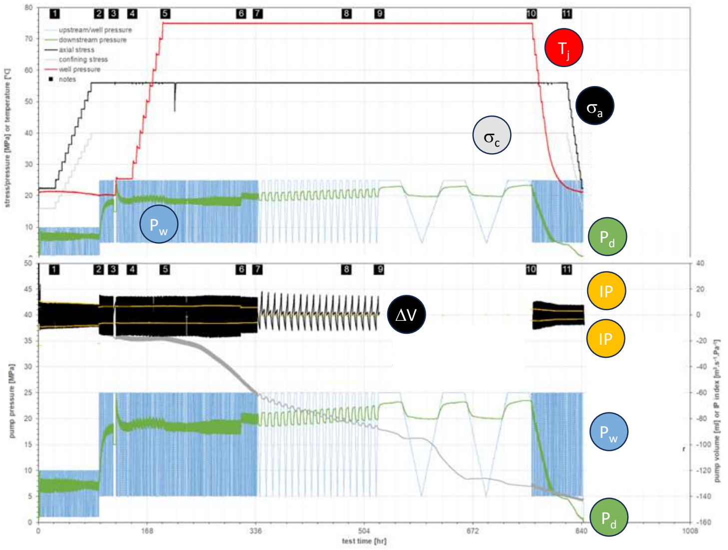
- **perf** casing perforations- no perfs (intact casing), partial perfs (intact cement), full perfs (hydraulic connect casing to sandstone)

Scaled down well system exposed to hydrogen: Sandstone pressure response during well pressure cycling



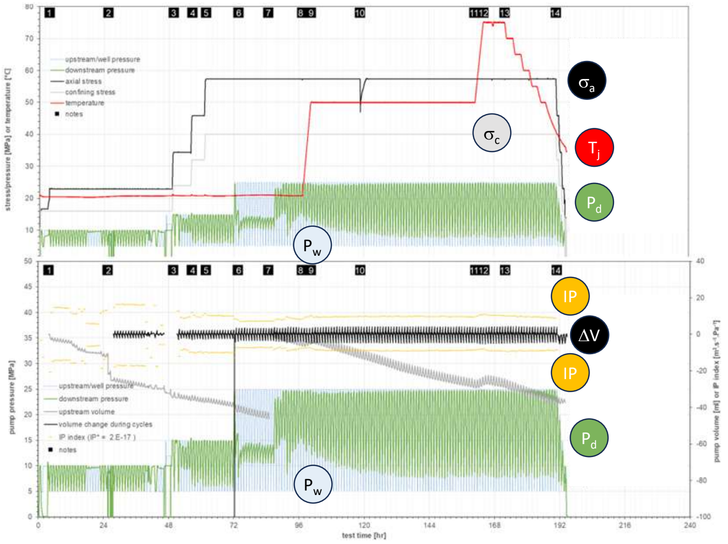
- Scaled down well system exposed to H_2 compared to systems that are not exposed or exposed to N_2
- Some changes in sandstone (downstream) pressure and IP index during prolonged cycling (195 cycles)
- The effect of cycling on injectivity and productivity may be due to inelastic sandstone deformation (compaction)
- **No *major* changes in injectivity and productivity**

Scaled down well system (no exposure, no perforations): Casing expansion/contraction during well pressure cycling



- Scaled down well system without casing perforations compared to systems with full perforations
- Much smaller pressure range in sandstone sample than for perforated casings (due to elastic deformation only as casing and sandstone are not hydraulically connected)
- Limited increase in sandstone (downstream) pressure during prolonged cycling (> 240 cycles) with different durations of cycle steps (20, 200, 2000 minutes)

Scaled down well system (no exposure, partial perfs): Cycling loading cement sheath during well pressure cycling



- Scaled down well system with partial casing perforations compared to systems with full or no perforations
- Change in sandstone pressure response to well pressure cycling after ~88 hrs (note 7) suggest fracturing of cement sheath
- Cyclic pressure differences between the casing and sandstone likely causes fracturing of the cement sheath and hydraulic connection between casing and sandstone
- Effects of experimental protocols and sample variability need to be addressed in additional (repeated) experiments
- **Observations suggest limited effects of well pressure cycling on integrity and durability of well systems for consolidated, well-cemented sandstone reservoirs**

Conclusions

- In general, no major effects of H_2 exposure or well pressure cycling on sandstone injectivity and productivity or integrity of scaled down well systems ***for investigated sandstones and under investigated conditions***

- Small decrease in injectivity/productivity for system exposed to H_2 may be due to inelastic deformation (compaction)

- The response of sandstone pressure to well pressure cycling changes significantly if casing is hydraulically connected to sandstone (full perforations or fractured cement sheath)

- Other causes for issues with H_2 injection/withdrawal: Formation damage due to change in chemical environment and ***combination of*** direct pressure, poro-elastic and thermo-elastic stressing

Impact of cyclic hydrogen storage on the reservoir and well system

[08] Geochemical reactions induced by hydrogen in the reservoir (Katriona Edlmann, University of Edinburgh)

GEOCHEMICAL REACTIONS INDUCED BY HYDROGEN IN THE RESERVOIR: EXPERIMENTAL OUTCOMES

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.

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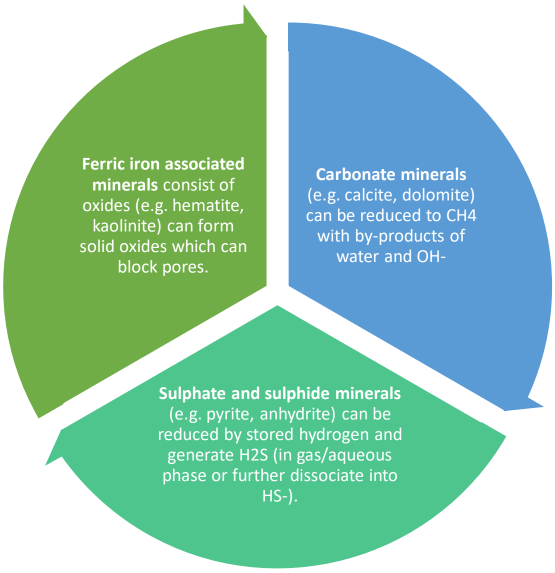
WP 2 GEOCHEMICAL REACTIONS

- Published studies consider geological hydrogen storage to be technically feasible; however, several reviews have identified challenges which must be addressed to prove the safe containment and necessary recovery efficiencies of hydrogen in porous reservoirs.
- Of particular concern are the promotion of geochemical reactions between the reservoir rocks, formation fluids, and stored hydrogen.
- The injection of hydrogen into a porous reservoir will change the reservoir, temperature, pressure and chemical equilibrium, which may induce geochemical reactions.
- **Objective of WP 2 was to address the uncertainties in the reactions of key minerals and understand the impact on permeability and storage site integrity**



Ferric iron associated minerals consist of oxides (e.g. hematite, kaolinite) can form solid oxides which can block pores.

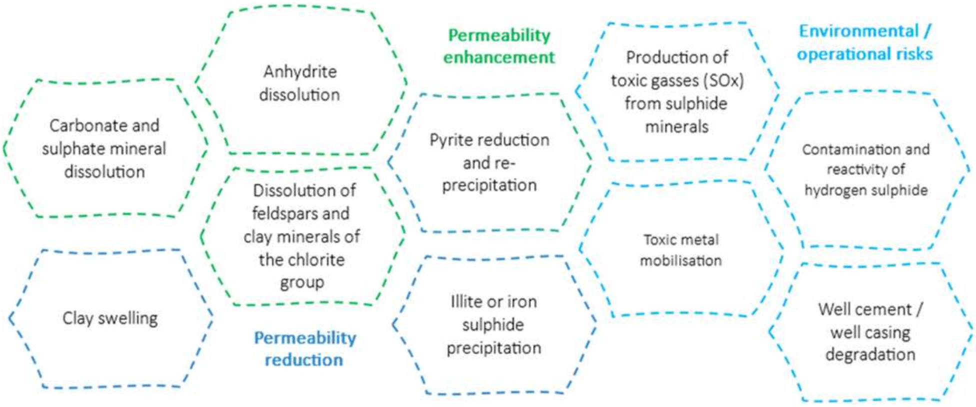
Carbonate minerals (e.g. calcite, dolomite) can be reduced to CH4 with by-products of water and OH-

Sulphate and sulphide minerals (e.g. pyrite, anhydrite) can be reduced by stored hydrogen and generate H2S (in gas/aqueous phase or further dissociate into HS-).

IMPACT OF HYDROGEN INDUCED GEOCHEMICAL REACTIONS

❖ These geochemical reactions may be detrimental to geological hydrogen storage through hydrogen consumption losses, compositional changes of the stored hydrogen, mineral precipitation and dissolution, and well cement and casing degradation which may impact reservoir integrity and recovery efficiencies.

❖ Hence, precise knowledge of the hydrogen-induced interactions between injected hydrogen and reservoir rocks and the resulting changes in the chemical and physical properties of the reservoir system is therefore a prerequisite for any secure operation of a underground hydrogen storage site.



Permeability enhancement

Carbonate and sulphate mineral dissolution

Anhydrite dissolution

Pyrite reduction and re-precipitation

Environmental / operational risks

Production of toxic gasses (SOx) from sulphide minerals

Contamination and reactivity of hydrogen sulphide

Dissolution of feldspars and clay minerals of the chlorite group

Toxic metal mobilisation

Clay swelling

Illite or iron sulphide precipitation

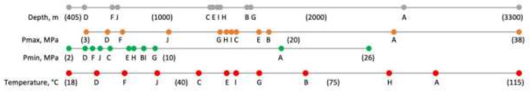
Well cement / well casing degradation

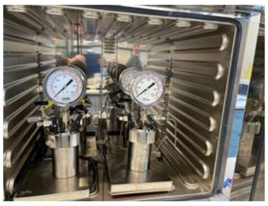
Permeability reduction

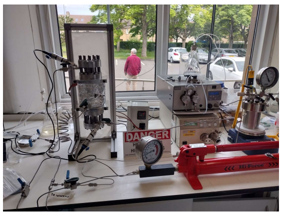
ASSESSMENT OF HYDROGEN-BRINE-RESERVOIR ROCK INTERACTIONS: STATIC BATCH REACTION EXPERIMENTS

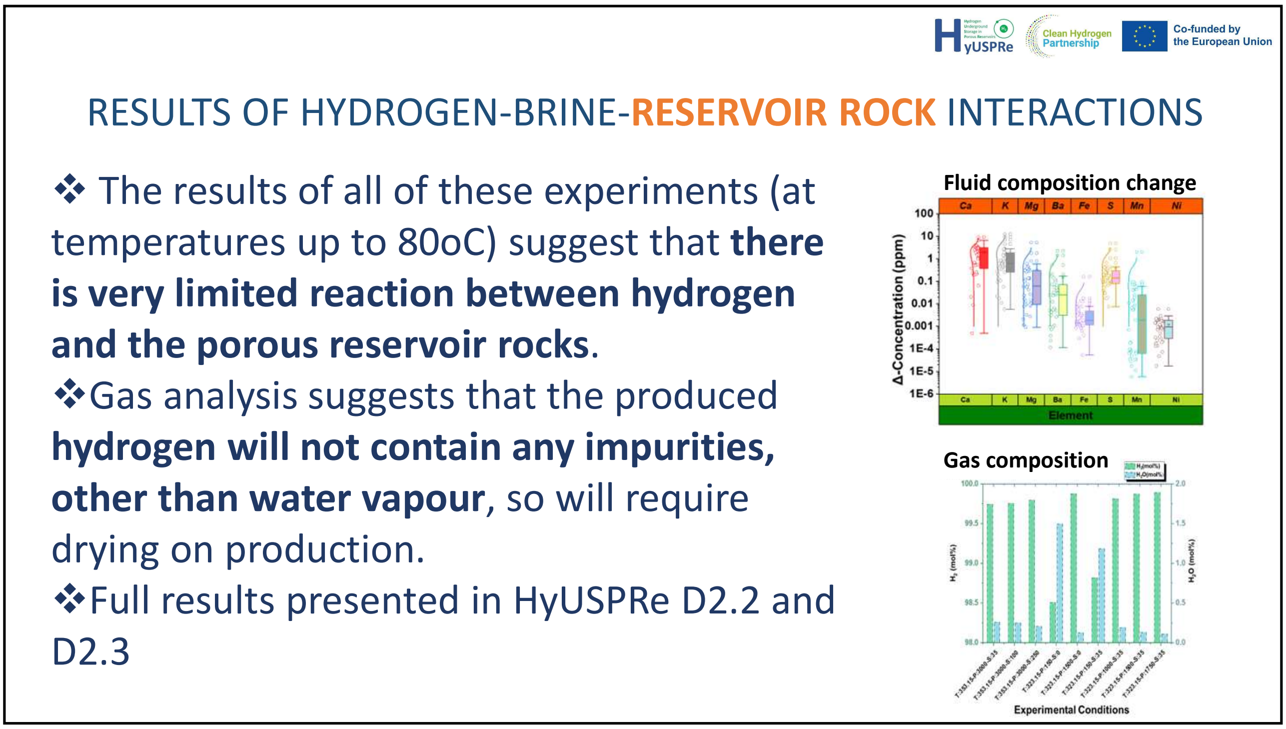
❖ Over 400 batch reactions experiments covering the range of rock types (reservoir and caprock), pure minerals and reservoir temperatures and pressures encountered across European gas storage sites have been completed.

HyUSPRe Field Site temperature and pressures







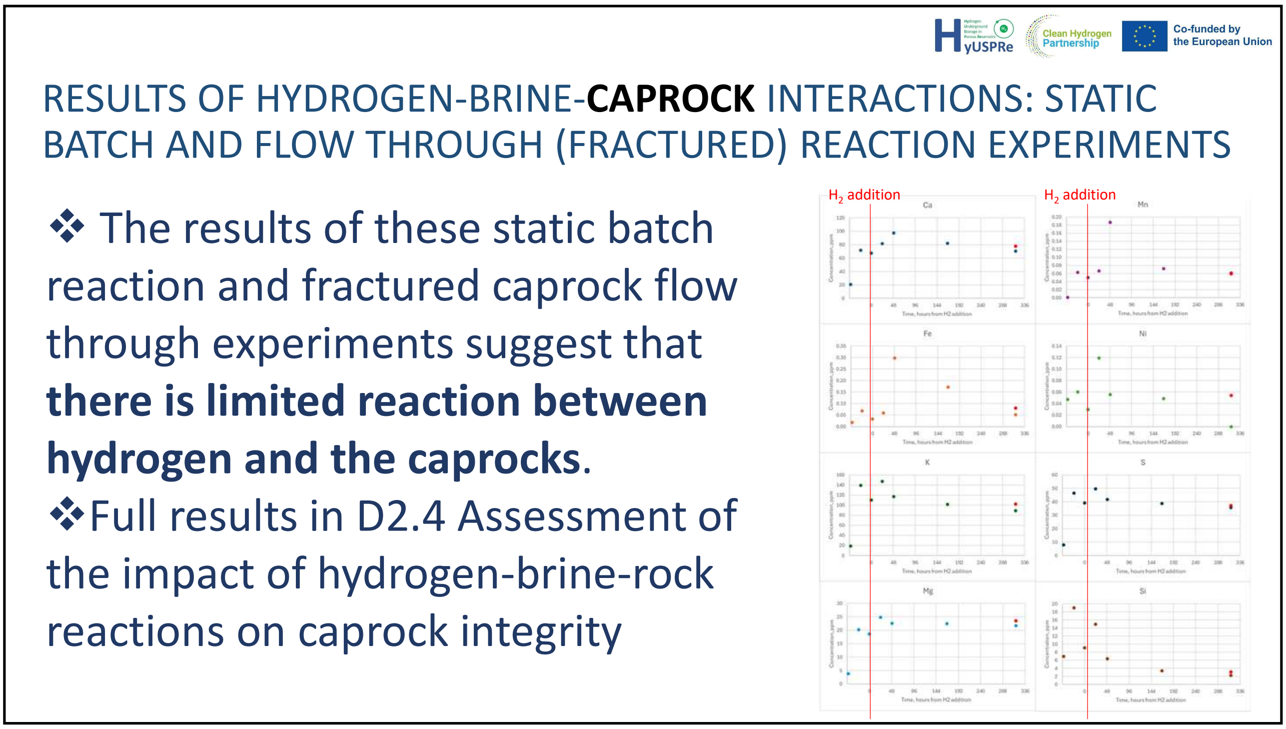


RESULTS OF HYDROGEN-BRINE-RESERVOIR ROCK INTERACTIONS

❖ The results of all of these experiments (at temperatures up to 80oC) suggest that **there is very limited reaction between hydrogen and the porous reservoir rocks**.

❖Gas analysis suggests that the produced **hydrogen will not contain any impurities, other than water vapour**, so will require drying on production.

❖Full results presented in HyUSPRe D2.2 and D2.3



RESULTS OF HYDROGEN-BRINE-**CAPROCK** INTERACTIONS: STATIC BATCH AND FLOW THROUGH (FRACTURED) REACTION EXPERIMENTS

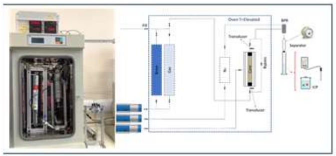
❖ The results of these static batch reaction and fractured caprock flow through experiments suggest that **there is limited reaction between hydrogen and the caprocks**.

❖Full results in D2.4 Assessment of the impact of hydrogen-brine-rock reactions on caprock integrity

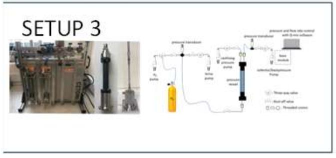
ASSESSMENT OF **PERMEABILITY CHANGES** DUE TO GEOCHEMICAL INTRATIONS DUING HYDROGEN INJECTION AND PRODUTION

- ❖ Three different experimental set-ups were used to evaluate permeability and porosity changes during hydrogen flow through porous rocks:
  - ❖**SETUP 1:** Alternating cycles of brine and then hydrogen flow and periods of fluid lock-in at 50 bar and room temperature
  - ❖**SETUP 2:** Alternating cycles of hydrogen saturated brine and hydrogen free brine, both partially pre-equilibrated with the rock at 50 bar and room temperature
  - ❖**SETUP 3**: µCT was utilised for a set of cyclic flow experiments (using hydrogen and synthetic brine and the Clashach Sandstone), allowing pore-scale images to be taken in-situ to monitor any changes.

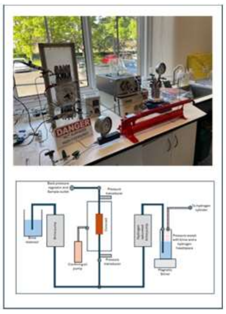
SETUP 2



SETUP 3

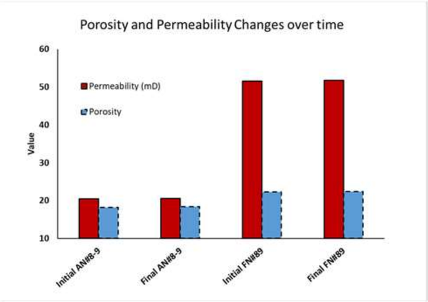


SETUP 1



ASSESSMENT OF **PERMEABILITY CHANGES** DUE TO GEOCHEMICAL INTRATIONS DUING HYDROGEN INJECTION AND PRODUTION

- ❖For all flow experiments an initial decrease in permeability was observed, likely due to residual trapping of the hydrogen gas rather than any geochemically induced physical changes to the pore network.
- ❖Effluent from all samples showed low (largely sub-ppm) elemental concentrations from mineral dissolution.
- ❖**Over time, no significant change in permeability or porosity resulting from geochemical interactions was observed during any of the runs undertaken**



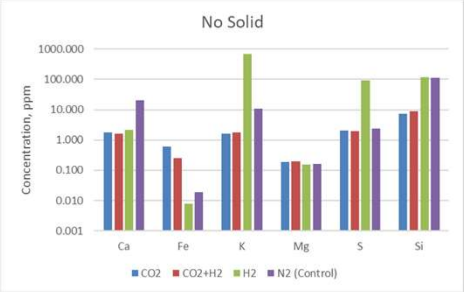
ASSESSMENT OF **IMPACT OF CO_2 AND CH_4** ON THE HYDROGEN - BRINE – ROCK SYSTEM

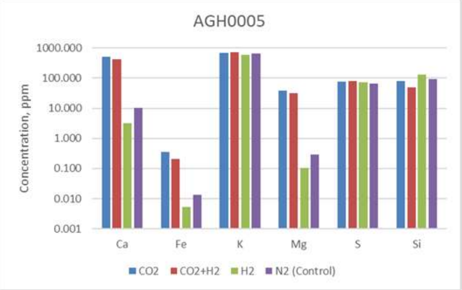
- During geological hydrogen storage, a cushion gas, such as natural gas, carbon dioxide, nitrogen, or hydrogen, is typically used to maintain reservoir pressures and minimize contact between hydrogen working gas and reservoir brine.
- Geochemical interactions within mixed gas systems are poorly understood.
- This work aims to explore the reactivity of reservoir and caprock samples with hydrogen and carbon dioxide or hydrogen and methane charged brine to better understand their geochemical impacts.
- Runs carried out using CO_2 or CH_4 only, H_2 only, or 50:50 $H_2/CO_2(CH_4)$ along with N_2 control runs

---

ASSESSMENT OF **IMPACT OF CO_2** ON THE HYDROGEN - BRINE – ROCK SYSTEM

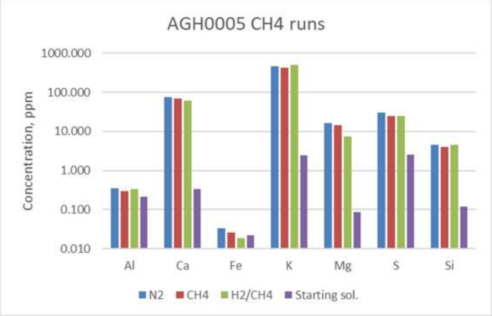
- **As might be expected the introduction of CO_2 has a relatively large impact on the geochemistry of the systems studied**:
  - Drop in brine pH following introduction of CO2 and CO_2/H_2 lead to dissolution of carbonate phases
- Results were broadly consistent between samples, with the dominant feature being enhanced concentrations of Ca, Fe and Mg (likely from carbonate dissolution) in runs utilising CO_2
- Similar concentrations between CO_2/CO_2+H_2 experiments and between H_2/N_2 experiments indicating CO_2 is the major driver of reactivity.





ASSESSMENT OF **IMPACT OF CH_4** ON THE HYDROGEN - BRINE – ROCK SYSTEM

- A single set of experiments investigating the influence of methane on hydrogen-brine-rock systems was carried out using a powdered reservoir sample and seawater strength brine and CH_4 and a CH_4/H_2 mixture, along with an N_2 control run
- Concentrations rise from the starting brine but to similar levels for all three gases/gas mixtures
- Similarity between CH_4, CH_4/H_2, and N_2 runs indicates that in this case **gas phase CH_4 has little influence on fluid-rock interaction**
- Full results in D2.5 Assessment of the impact of CH_4 and CO_2 on the geochemical response of the hydrogen-brine-rock system



THERE IS ONE AREA OF INTEREST = Potential for H_2S generation from pyrite reduction during hydrogen storage

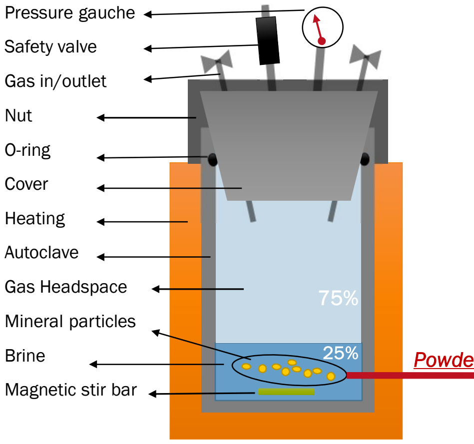
- The presence of hydrogen in a reservoir containing pyrite may have the potential to generate H_2S:

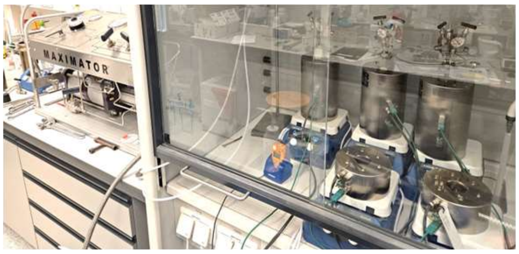
$$FeS_2 + H_2 = FeS + H_2S\ (pyrite\ reduction\ to\ pyrrhotite)$$

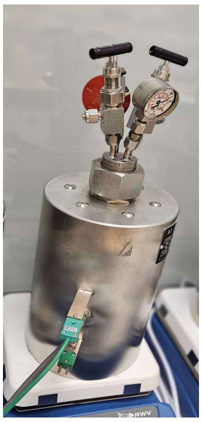
- While experiments on pyrite reactivity with hydrogen at temperatures below 80oC run at Edinburgh did not observe pyrite reactions, they were observed at temperatures above 100oC
  - I will now pass to my colleagues at TNO to describe this work and these important findings in more detail.

Risk of H_2S generation from reduction of pyrite by H_2

- **Stirred batch experiments (at TNO, Eindhoven, NL)**
  - Abiotic reaction under high pressure of pure hydrogen
  - HSE-compliant experimental set-up: 200ml autoclave, H_2 and H_2S resistant coating, max 150 °C, max 350 bar
  - Sample analysis by post mortem XRD with Rietveld refinement and SEM equipped with EDX





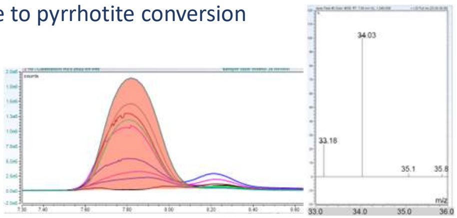


Risk of H_2S generation from reduction of pyrite by H_2

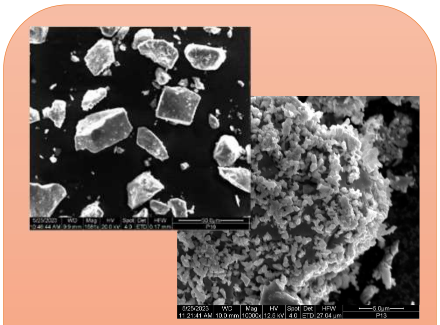
- **Characterisation methods and analyses on gas headspace, liquids and powder**
  - Particle characterisation by Mastersizer and BET analysis
  - GC-MS is used to detect H_2S in the gas sample of the headspace
  - SEM with EDX visualize the pyrrhotite crystal growth
  - XRD Rietveld quantifies the pyrite to pyrrhotite conversion
  - pH measurement of the liquids

Pyrite → Pyrrhotite

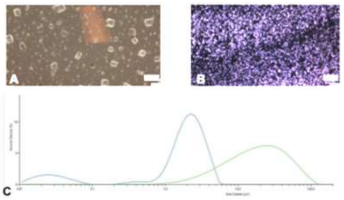
$FeS_2 + H_2 \rightleftharpoons FeS + H_2S$



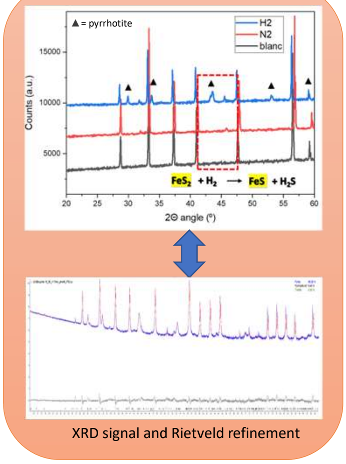
Example of GC-MS signal of H_2S (pH 9, T = 150°C, P = 50 bar)



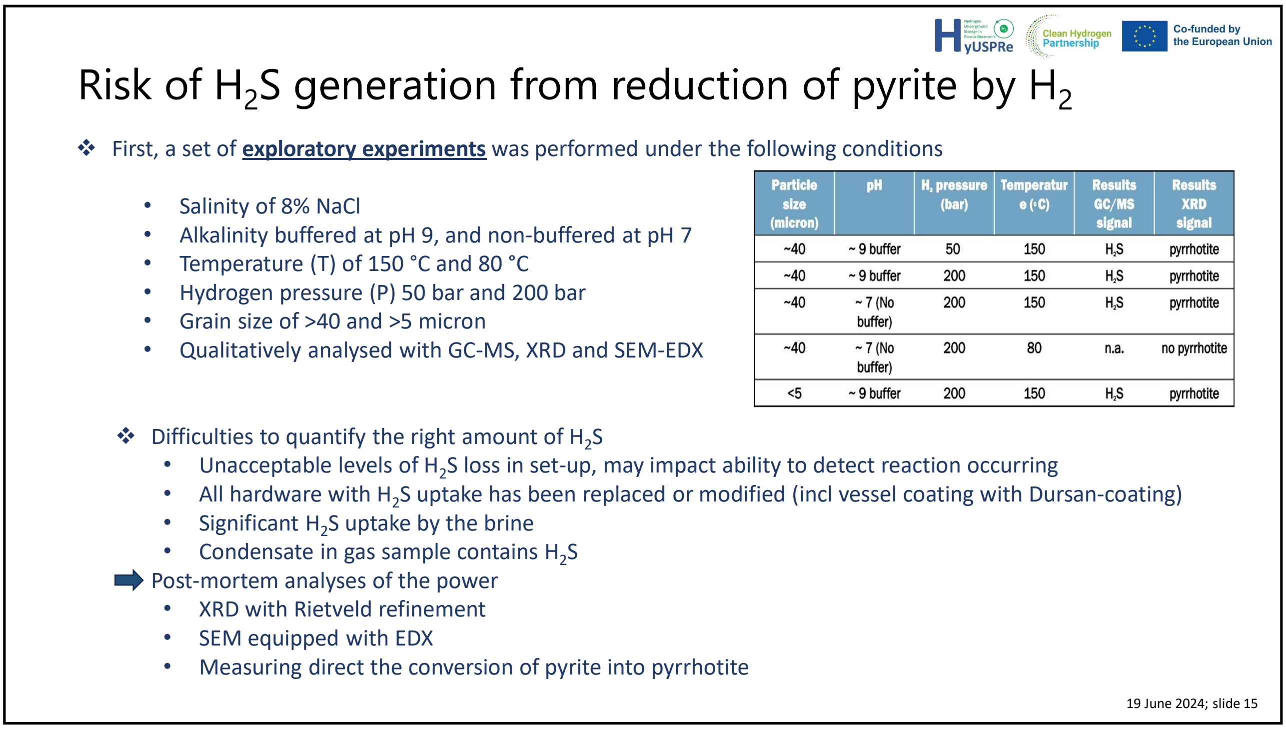
Example of SEM picture, reacted (pH 9, T = 150°C, P = 200 bar) and unreacted powder (right)



Particle size distribution of >5 and >40 micron fractions



XRD signal and Rietveld refinement



Risk of H_2S generation from reduction of pyrite by H_2

❖ First, a set of **exploratory experiments** was performed under the following conditions

- Salinity of 8% NaCl
- Alkalinity buffered at pH 9, and non-buffered at pH 7
- Temperature (T) of 150 °C and 80 °C
- Hydrogen pressure (P) 50 bar and 200 bar
- Grain size of >40 and >5 micron
- Qualitatively analysed with GC-MS, XRD and SEM-EDX

Particle size (micron)	pH	H_2 pressure (bar)	Temperature (°C)	Results GC/MS signal	Results XRD signal
~40	~ 9 buffer	50	150	H_2S	pyrrhotite
~40	~ 9 buffer	200	150	H_2S	pyrrhotite
~40	~ 7 (No buffer)	200	150	H_2S	pyrrhotite
~40	~ 7 (No buffer)	200	80	n.a.	no pyrrhotite
<5	~ 9 buffer	200	150	H_2S	pyrrhotite

❖ Difficulties to quantify the right amount of H_2S
  - Unacceptable levels of H_2S loss in set-up, may impact ability to detect reaction occurring
  - All hardware with H_2S uptake has been replaced or modified (incl vessel coating with Dursan-coating)
  - Significant H_2S uptake by the brine
  - Condensate in gas sample contains H_2S

➡ Post-mortem analyses of the power
  - XRD with Rietveld refinement
  - SEM equipped with EDX
  - Measuring direct the conversion of pyrite into pyrrhotite

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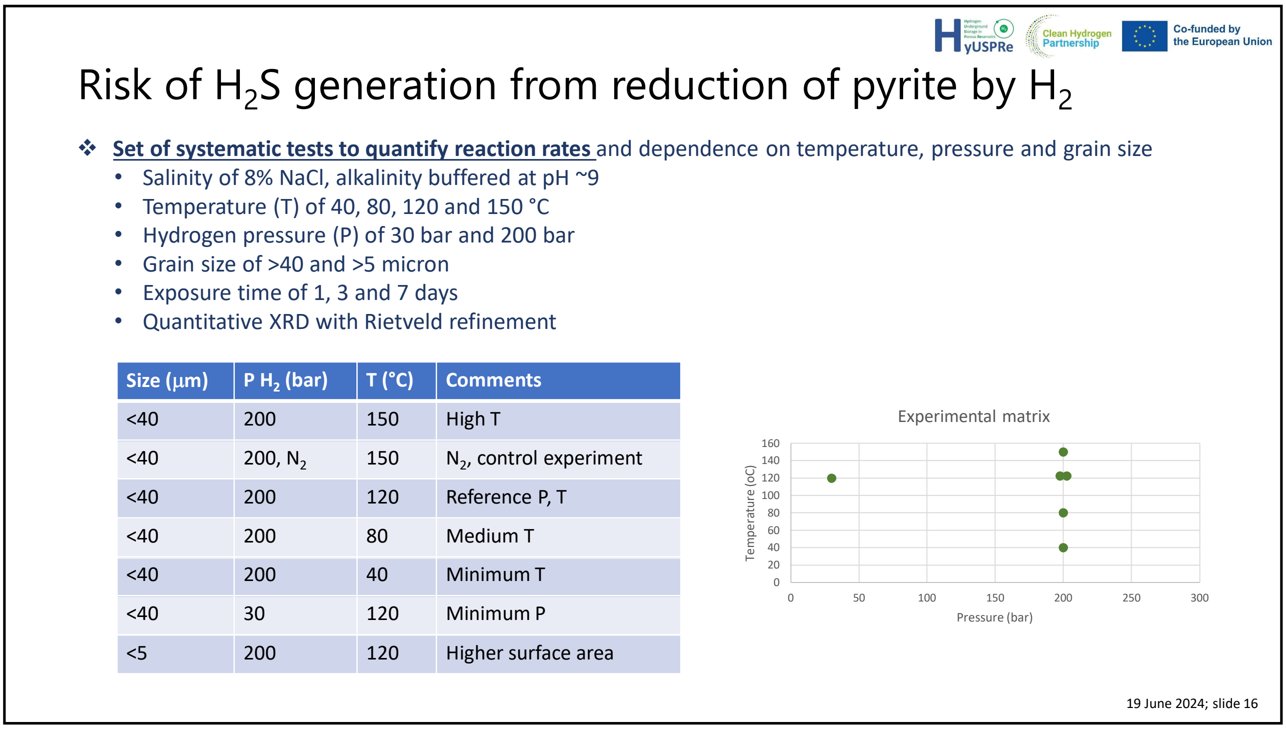


Risk of H_2S generation from reduction of pyrite by H_2

❖ **Set of systematic tests to quantify reaction rates** and dependence on temperature, pressure and grain size
  - Salinity of 8% NaCl, alkalinity buffered at pH ~9
  - Temperature (T) of 40, 80, 120 and 150 °C
  - Hydrogen pressure (P) of 30 bar and 200 bar
  - Grain size of >40 and >5 micron
  - Exposure time of 1, 3 and 7 days
  - Quantitative XRD with Rietveld refinement

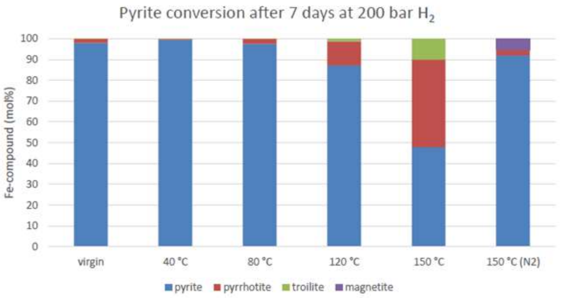
Size (µm)	P H_2 (bar)	T (°C)	Comments
<40	200	150	High T
<40	200, N_2	150	N_2, control experiment
<40	200	120	Reference P, T
<40	200	80	Medium T
<40	200	40	Minimum T
<40	30	120	Minimum P
<5	200	120	Higher surface area

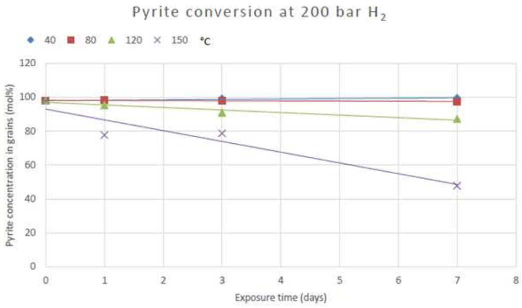
Risk of H_2S generation from reduction of pyrite by H_2

- **Results**
  - **A strong temperature effect on the reaction rate is observed**
  - At 150 °C over 50% conversion has been observed in 7 days while at 80 °C only an indication of a small conversion can be concluded
  - The N_2 control experiment shows no conversion of pyrite into pyrrhotite
  - Also Troilite, another Ironmonosulfide (FeS) has been formed

Pyrite → Pyrrhotite

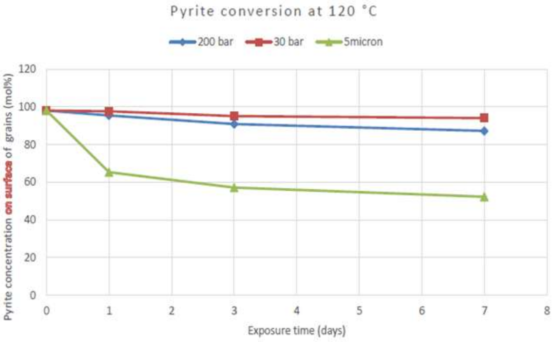
$FeS_2 + H_2 \rightleftharpoons FeS + H_2S$





Risk of H_2S generation from reduction of pyrite by H_2

- **Results**
  - **Higher pressures slightly increase the reaction rate**
    - 13% conversion was observed at 200 bar compared to 6% conversion at 30 bar, both at 120°C
  - **Smaller particle sizes significantly increase the conversion rate**
    - 5 micron particles have a larger available surface area and showed 48% conversion, compared to 13% conversion for particles up to 40 microns, under the same conditions (120°C and 200 bar)



Risk of H_2S generation from reduction of pyrite by H_2

❖ **Conclusions**

- **Strong temperature effect on reaction rate is observed**
  - After 7 days, 200 bar, pH ~9:
    - Over 50% conversion at 150 °C
    - Low but detectable conversion at 80 °C
    - Unanswered (yet): is there an absolute lower T limit for the reaction?
- **Higher pressures slightly increase the reaction rate**
  - After 7 days, at 120 °C, pH ~9:
    - 13% vs. 6% conversion at resp 200 and 30 bar
  - At higher P more H2 dissolves into brine, and penetration depth into particles may be increased
- **Smaller particle sizes significantly increase the conversion rate – effect of surface area**
  - After 7 days, at 120 °C and 200 bar, pH ~9:
    - 48% vs. 13% conversion for resp <5 and <40 micron particles
  - Conversion is likely a self-inhibiting (limiting) surface reaction
  - Conversion to pyrrhotite takes place at the surface of the pyrite grains

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Risk of H_2S generation from reduction of pyrite by H_2

❖ **Calculated rates of H_2S production and associated H_2 loss** [120 °C, 200 bar, pH ~9]

- H_2S production rates (calculated): 4-8 mg/day/g pyrite with <40 micron particles
  - Corresponding H_2 loss of 0.2-0.4 mg/day
- H_2S production rates (calculated): 19-95 mg/day/g pyrite with <5 micron particles
  - Corresponding H_2 loss of 1-6 mg/day
- Amount of “reactive” pyrite available governed by surface area and penetration depth of H_2 into particles

❖ **Recommendations (for future work)**

- Additional experiments to gain more data points to develop a rate law that parameterizes the kinetics
- Long term exposure time to study conditions at low reaction rate (Temperature <120 °C)
- Study pH dependency of the reaction
- Collect rock samples to determine the amount of pyrite and the available surface area to react
- More research on ratio of H_2S over gas phase and liquid phase to model how much H_2S will be produced
- Additional experiments with gas mixtures and mineral mixtures

WP2 Dissemination activities

WP2 Deliverables

- D2.1: Database of mineral reaction rates with hydrogen and their dependence on temperature and pressure
- D2.2; Assessment of the potential for contamination / H_2S souring of produced hydrogen over the lifetime of a storage site
- D2.3 Assessment of the impact of chemical reactions on reservoir pore space and mechanical integrity over time
- D2.4 Assessment of the impact of hydrogen-brine-rock reactions on caprock integrity.
- D2:5 Report on the assessment of the impact of CH_4 and CO_2 on the geochemical response of the hydrogen-brine-rock system

WP2 Scientific publications

- Hassanpouryouzband, A., Adie, K., Cowen, T., Thaysen, E. M., Heinemann, N., Butler, I. B., Wilkinson, M., & Edlmann, K. (2022). Geological hydrogen storage: Geochemical reactivity of hydrogen with sandstone reservoirs. ACS Energy Letters, 7(7), 2203–2210. https://doi.org/10.1021/acsenergylett.2c01024
- Aftab, A., Hassanpouryouzband, A., Martin, A., Kendrick, J. E., Thaysen, E. M., Heinemann, N., ... & Edlmann, K. (2023). Geochemical Integrity of Wellbore Cements during Geological Hydrogen Storage. Environ. Sci. Technol. Lett. https://doi.org/10.1021/acs.estlett.3c00303
- Thaysen, E. M., Armitage, T., Slabon, L., Hassanpouryouzband, A., & Edlmann, K. (2023). Microbial risk assessment for underground hydrogen storage in porous rocks. Fuel, 352, 128852. https://doi.org/10.1016/j.fuel.2023.128852
- Heinemann, N., Wilkinson, M., Adie, K., Edlmann, K., Thaysen, E. M., Hassanpouryouzband, A., Haszeldine, R. S. (2022). Cushion gas in hydrogen storage—A costly CAPEX or a valuable resource for energy crises? Hydrogen, 3(4), 550-563. https://doi.org/10.3390/hydrogen3040035
- Thaysen, E. M., Butler, I. B., Hassanpouryouzband, A., Freitas, D., Alvarez-Borges, F., Krevor, S., Heinemann, N., Atwood, R., & Edlmann, K. (2022). Pore-scale imaging of hydrogen displacement and trapping in porous media. International Journal of Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2022.10.153
- Peecock, A., Edlmann, K., Mouli-Castillo, J., Martinez-Felipe, A., & McKenna, R. (2022). Mapping hydrogen storage capacities of UK offshore hydrocarbon fields and investigating potential synergies with offshore wind. Geological Society, London, Special Publications, 528. https://doi.org/10.1144/SP528-2022-40

Impact of cyclic hydrogen storage on the reservoir and well system

[09] Microbiological activity in the reservoir under hydrogen storage conditions (Diana Sousa, Wageningen University)

HYUSPRE – FINAL CONFERENCE
19 JUNE 2024 | TNO, UTRECHT

MICROBIOLOGICAL ACTIVITY IN THE RESERVOIR UNDER HYDROGEN STORAGE CONDITIONS (WP3)

DIANA SOUSA | WU

Hydrogen
Underground
Storage in
Porous Reservoirs
HyUSPRe

Clean Hydrogen Partnership

Co-funded by the European Union

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.

This document reflects the views of the author(s) and does not necessarily reflect the views or policy of the European Commission. Whilst efforts have been made to ensure the accuracy and completeness of this document, the HyUSPRe consortium shall not be liable for any errors or omissions, however caused.

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WAGENINGEN UNIVERSITY & RESEARCH

Bart Lomans

Clean Hydrogen Partnership
Co-funded by the European Union

CLT

Microbial life in the subsurface

- Subsurface environment harbors extreme conditions:
  - High temperature, pressure and salinity
  - Limited nutrients and energy source
  - Limited pore sizes
- Life is possible until at least a depth of 5000 m
- Deep biosphere composes 2–19% of the Earth's total biomass
- Microbial cell number & diversity
  - Cell numbers between 8.65×10^{4} - 1.01×10^{6}/g rock
  - Decreases over the depth
  - Depends on environmental conditions
- Most microbes in the subsurface are in dormant state

The "Adopt A Microbe" project, American Geophysical Union

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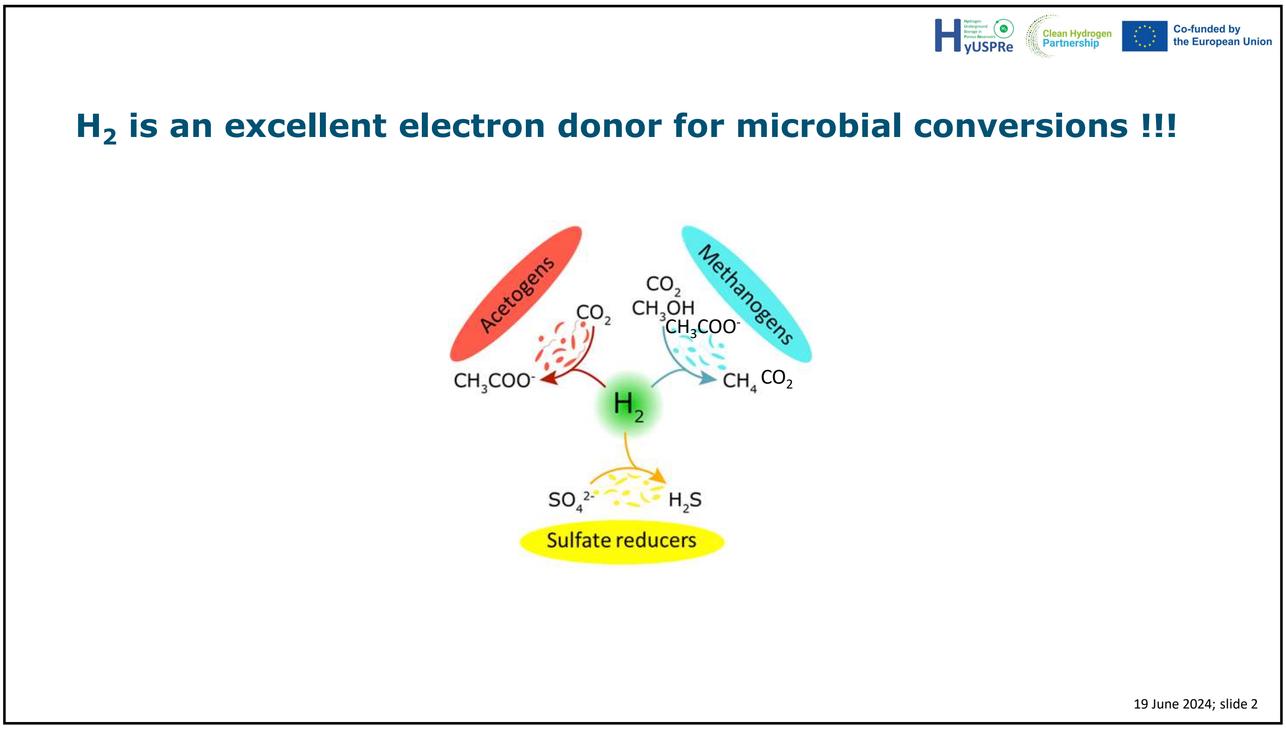
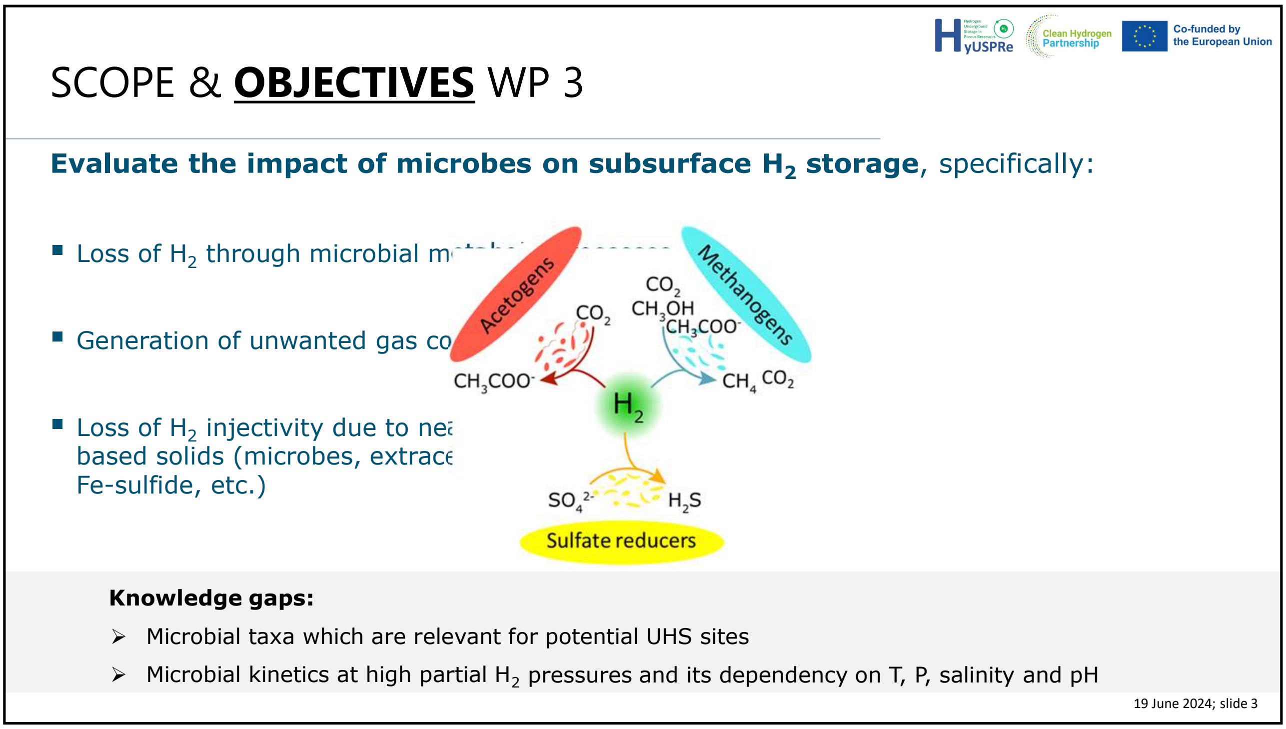


H_2 is an excellent electron donor for microbial conversions !!!

19 June 2024; slide 2



SCOPE & **OBJECTIVES** WP 3

Evaluate the impact of microbes on subsurface H_2 storage, specifically:

- Loss of H_2 through microbial m
- Generation of unwanted gas co
- Loss of H_2 injectivity due to nea based solids (microbes, extrace Fe-sulfide, etc.)

Knowledge gaps:

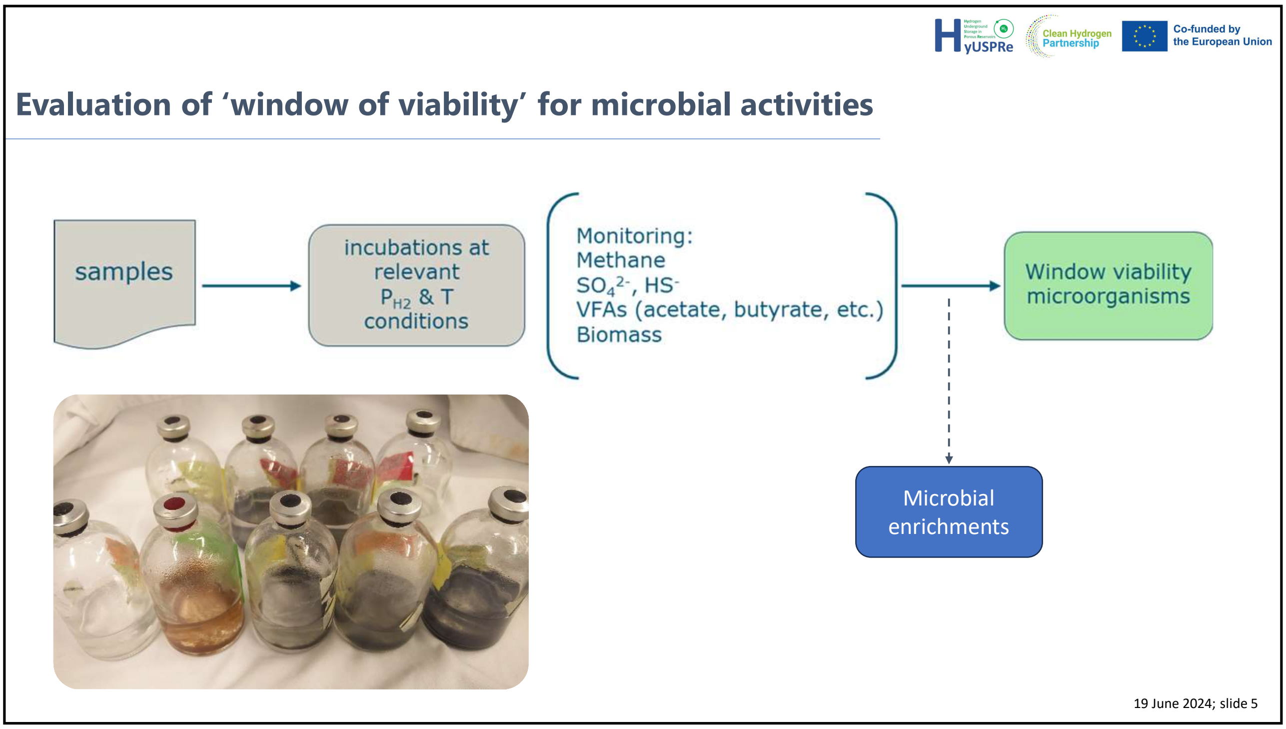
- Microbial taxa which are relevant for potential UHS sites
- Microbial kinetics at high partial H_2 pressures and its dependency on T, P, salinity and pH

19 June 2024; slide 3

SUMMARY OF ACTIVITIES WP 3

- Evaluation of 'window of viability' for microbial activities → **29 samples** porous reservoirs from 4 partners
- Kinetics of microbial growth & modelling
- Competition dynamics between different microbial metabolisms

} **5 selected sites**



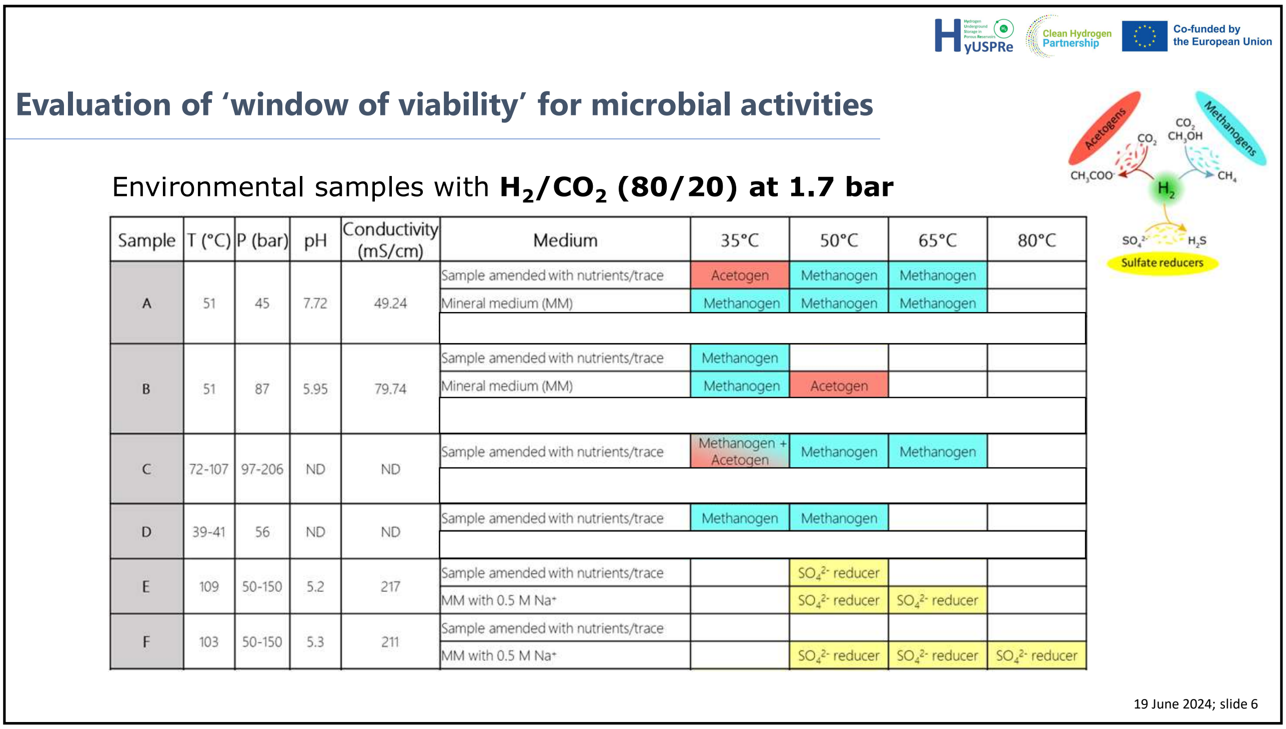
Evaluation of 'window of viability' for microbial activities

samples → incubations at relevant P_{H2} & T conditions

Monitoring:
Methane
SO_4^{2-}, HS^-
VFAs (acetate, butyrate, etc.)
Biomass

→ Window viability microorganisms

Microbial enrichments



HyUSPRe

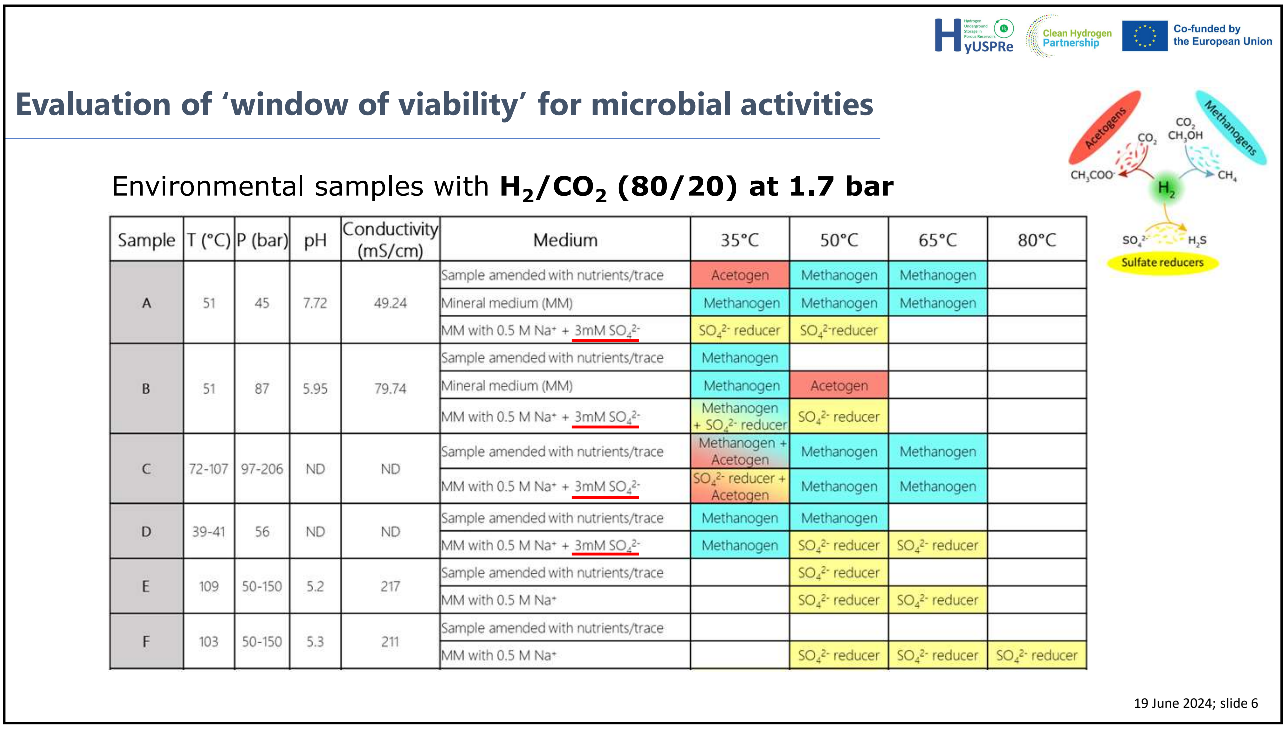
Clean Hydrogen Partnership

Co-funded by the European Union

Evaluation of 'window of viability' for microbial activities

Environmental samples with H_2/CO_2 (80/20) at 1.7 bar

Sample	T (°C)	P (bar)	pH	Conductivity (mS/cm)	Medium	35°C	50°C	65°C	80°C
A	51	45	7.72	49.24	Sample amended with nutrients/trace	Acetogen	Methanogen	Methanogen	
					Mineral medium (MM)	Methanogen	Methanogen	Methanogen	
B	51	87	5.95	79.74	Sample amended with nutrients/trace	Methanogen			
					Mineral medium (MM)	Methanogen	Acetogen		
C	72-107	97-206	ND	ND	Sample amended with nutrients/trace	Methanogen + Acetogen	Methanogen	Methanogen	
D	39-41	56	ND	ND	Sample amended with nutrients/trace	Methanogen	Methanogen		
E	109	50-150	5.2	217	Sample amended with nutrients/trace		SO_4^{2-} reducer		
					MM with 0.5 M Na^+		SO_4^{2-} reducer	SO_4^{2-} reducer	
F	103	50-150	5.3	211	Sample amended with nutrients/trace				
					MM with 0.5 M Na^+		SO_4^{2-} reducer	SO_4^{2-} reducer	SO_4^{2-} reducer



HyUSPRe

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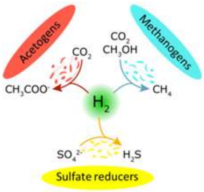
A	51	45	7.72	49.24	Sample amended with nutrients/trace	Acetogen	Methanogen	Methanogen	
					Mineral medium (MM)	Methanogen	Methanogen	Methanogen	
					MM with 0.5 M Na^+ + 3mM SO_4^{2-}	SO_4^{2-} reducer	SO_4^{2-}reducer		
B	51	87	5.95	79.74	Sample amended with nutrients/trace	Methanogen			
					Mineral medium (MM)	Methanogen	Acetogen		
					MM with 0.5 M Na^+ + 3mM SO_4^{2-}	Methanogen + SO_4^{2-} reducer	SO_4^{2-} reducer		
C	72-107	97-206	ND	ND	Sample amended with nutrients/trace	Methanogen + Acetogen	Methanogen	Methanogen	
					MM with 0.5 M Na^+ + 3mM SO_4^{2-}	SO_4^{2-} reducer + Acetogen	Methanogen	Methanogen	
D	39-41	56	ND	ND	Sample amended with nutrients/trace	Methanogen	Methanogen		
					MM with 0.5 M Na^+ + 3mM SO_4^{2-}	Methanogen	SO_4^{2-} reducer	SO_4^{2-} reducer	
E	109	50-150	5.2	217	Sample amended with nutrients/trace		SO_4^{2-} reducer		
					MM with 0.5 M Na^+		SO_4^{2-} reducer	SO_4^{2-} reducer	
F	103	50-150	5.3	211	Sample amended with nutrients/trace				
					MM with 0.5 M Na^+		SO_4^{2-} reducer	SO_4^{2-} reducer	SO_4^{2-} reducer

Evaluation of ‘window of viability’ for microbial activities



Environmental samples with **H_2 at 1.7 bar (no added C-source)**

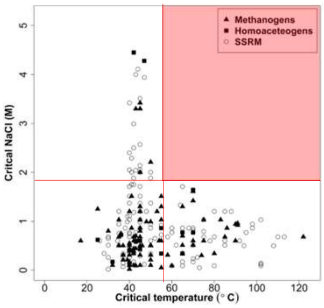
Sample	T (°C)	P (bar)	pH	Conductivity (mS/cm)	35°C	50°C	65°C	80°C
A	51	45	7.72	49.24	Methanogen	Methanogen	Methanogen	
B	51	87	5.95	79.74				
C	72-107	97-206	ND	ND	Methanogen	Methanogen	Methanogen	Methanogen
D	39-41	56	ND	ND		SO_4^{2-} reducer	SO_4^{2-} reducer	

Evaluation of ‘window of viability’ for microbial activities

Microbial survivability limits under relevant subsurface H_2 storage conditions

Parameters	Microbial optimum & limit	Methanogens	Sulfate reducers	Acetogens
Temperature (H_2 storage: 22.5-100°C)	Optimum Limits	15-98°C 122°C	10-106°C 113°C	20-30°C 72°C
Pressure (H_2 storage: 1-50 MPa)	Optimum		0-30/50 MPa	
Salinity (H_2 storage: 0-5 M NaCl)	Optimum Limits	0-0.77 M NaCl 3.4 M NaCl	0-0.4 M NaCl 4.2 M NaCl	0-0.4 M NaCl 4.4 M NaCl
pH	Optimum Limits	4-9.5 4-10	 1-10	NA 3.6-10.7

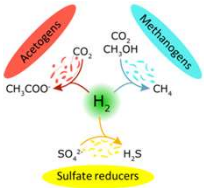
(Thaysen et al., 2021, doi: 0.1016/j.rser.2021.111481)



Temperature and salinity are the most constraining factors

- Temperature alone: upper life limit is 122°C
- Combination of temperature and salinity: >55°C, and >1.7 M NaCl

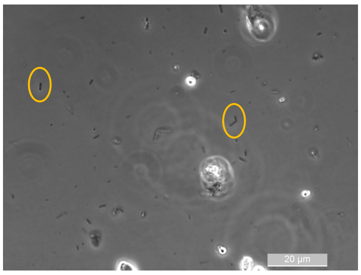
Evaluation of 'window of viability' for microbial activities



"Mixed-Inoculum" incubation with **H_2 at 1.7 bar**

Medium	35°C	50°C	65°C	80°C
MM with 0.5 M Na^+ + 3mM SO_4^{2-}	Methanogen + SO_4^{2-} reducer	Methanogen + SO_4^{2-} reducer	Methanogen	
MM with 2 M Na^+ + 3mM SO_4^{2-}	Methanogen + SO_4^{2-} reducer	Methanogen + SO_4^{2-} reducer	SO_4^{2-} reducer	

2 mM sulfide
produced during
7 months of enrichment



→ 16S rRNA gene: Peptococcaceae (amongst others)

Redefines the currently known window of viability to the combination of at least >65°C, and >2 M NaCl

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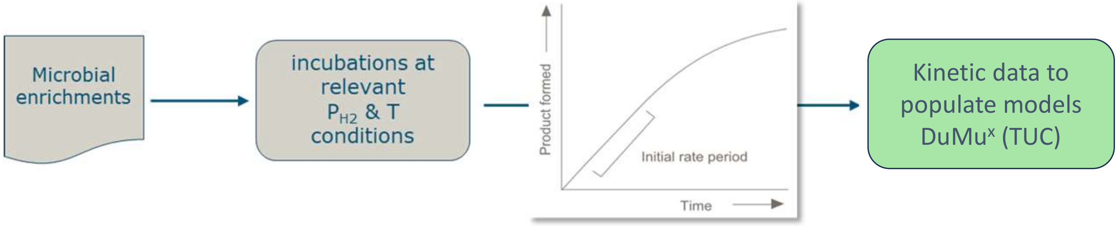
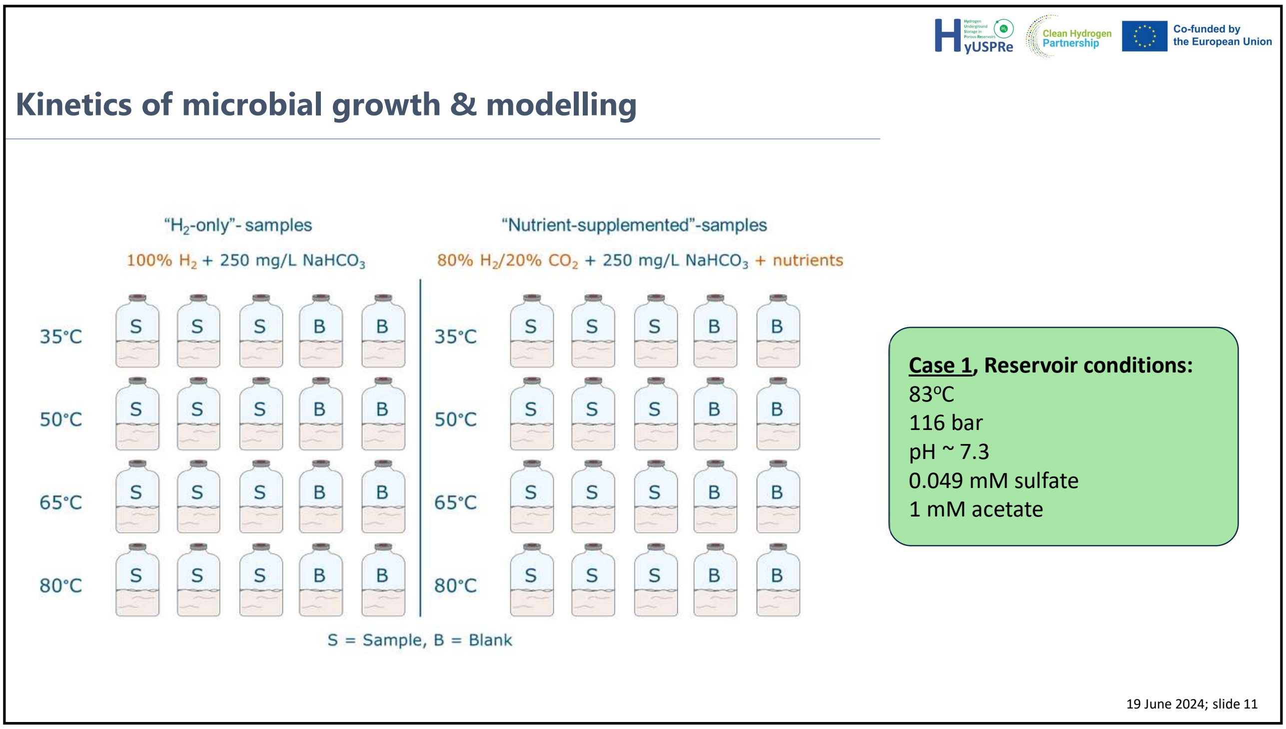
Kinetics of microbial growth & modelling



Microbial enrichments

incubations at relevant P_{H2} & T conditions

Kinetic data to populate models DuMu^x (TUC)



Kinetics of microbial growth & modelling

“H_2-only”- samples

100% H_2 + 250 mg/L $NaHCO_3$

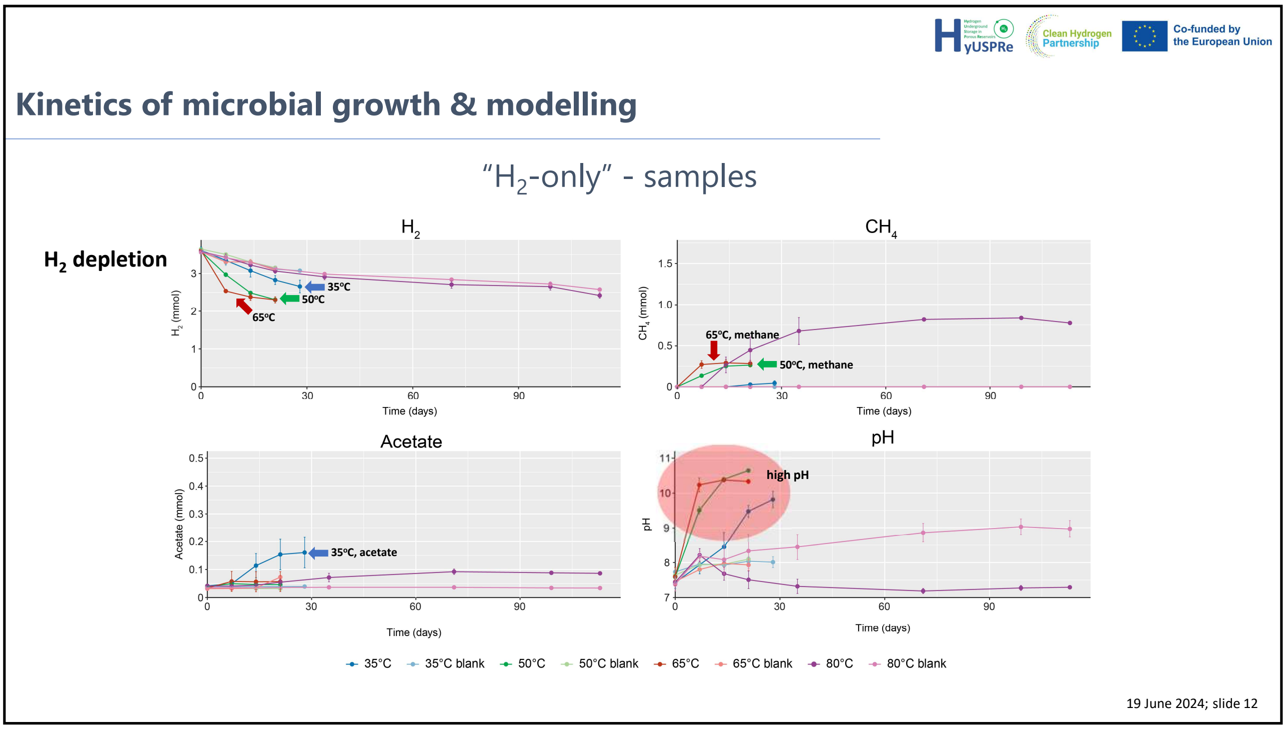
“Nutrient-supplemented”-samples

80% H_2/20% CO_2 + 250 mg/L $NaHCO_3$ + nutrients

S = Sample, B = Blank

Case 1, Reservoir conditions:
83ºC
116 bar
pH ~ 7.3
0.049 mM sulfate
1 mM acetate

19 June 2024; slide 11

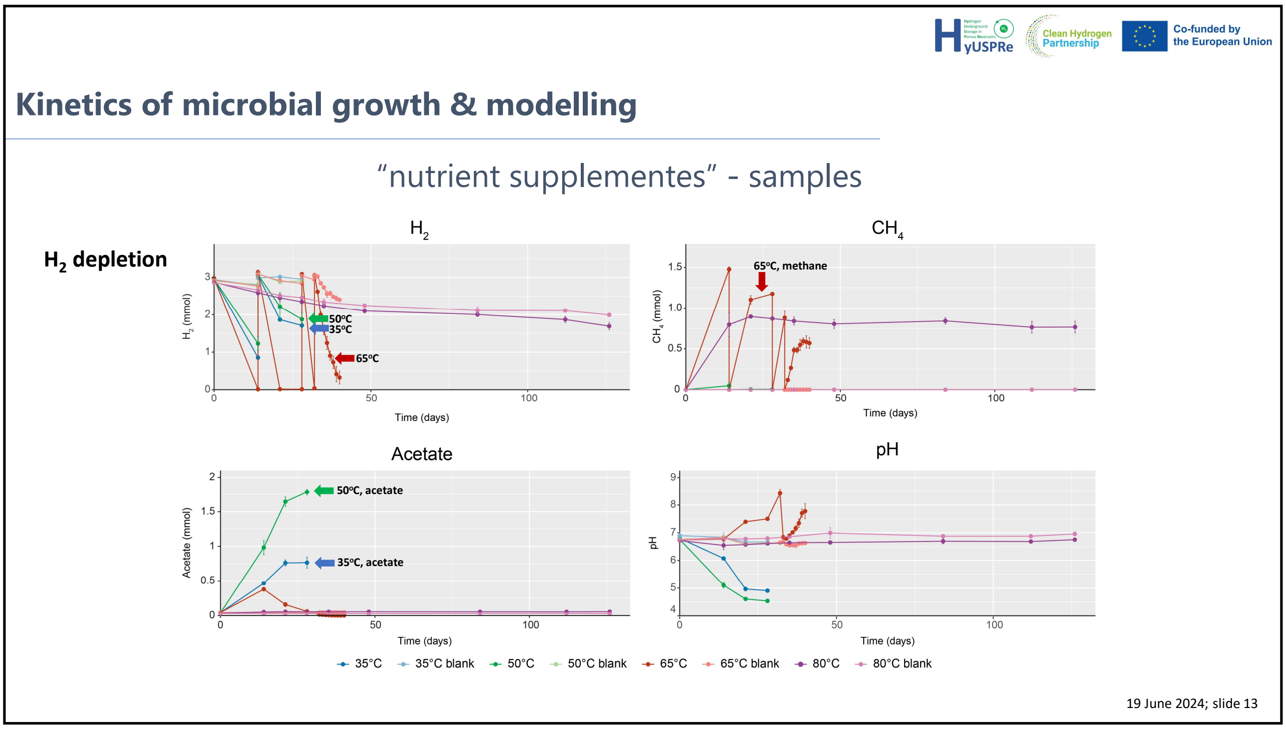


Kinetics of microbial growth & modelling

“H_2-only” - samples

H_2 depletion

19 June 2024; slide 12



HyUSPRe

Clean Hydrogen Partnership

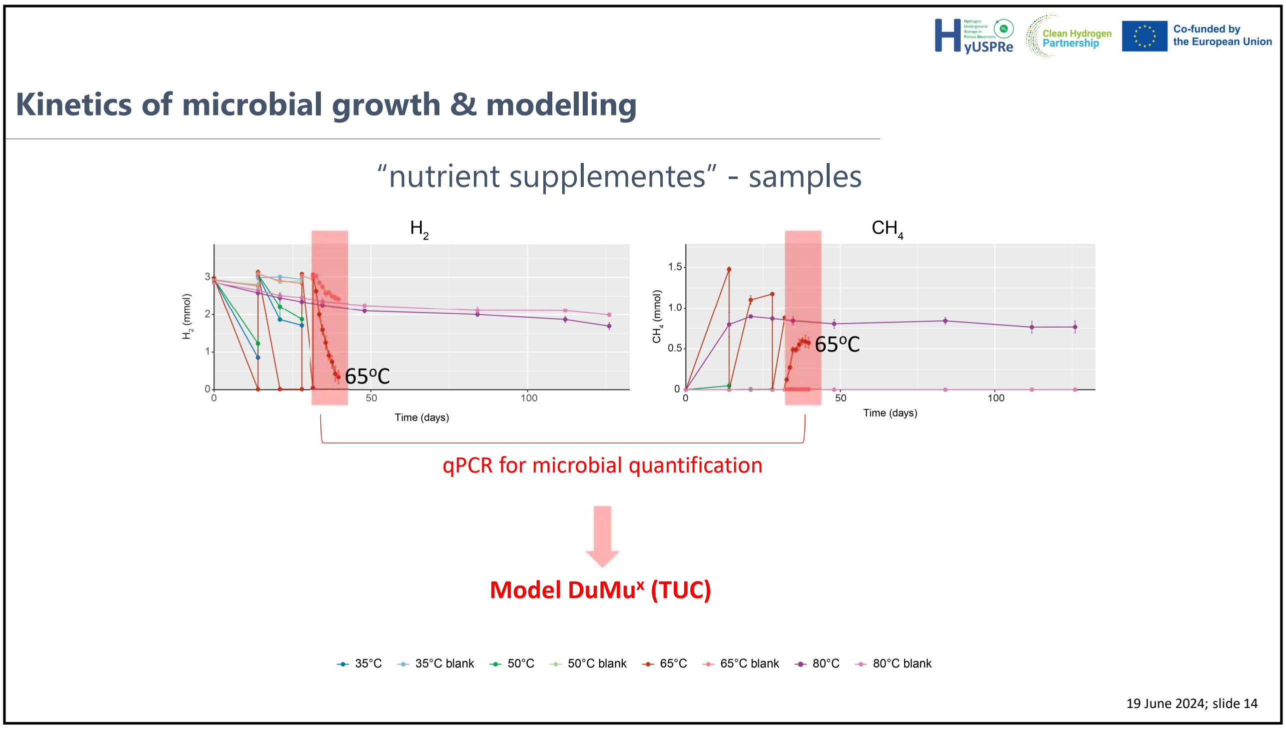
Co-funded by the European Union

Kinetics of microbial growth & modelling

"nutrient supplementes" - samples

H_2 depletion

19 June 2024; slide 13



HyUSPRe

Clean Hydrogen Partnership

Co-funded by the European Union

Kinetics of microbial growth & modelling

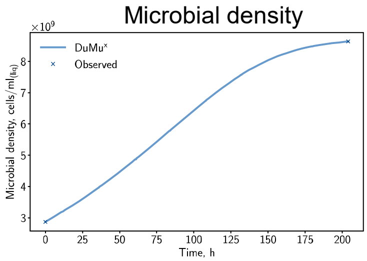
"nutrient supplementes" - samples

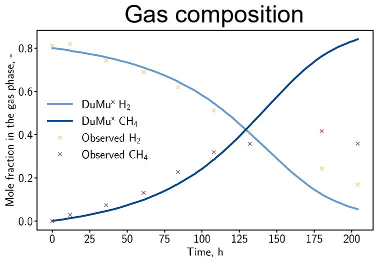
qPCR for microbial quantification

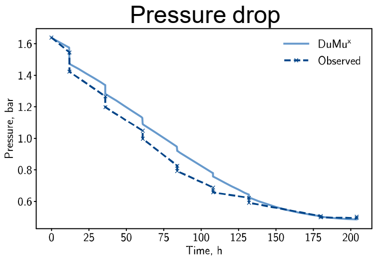
Model DuMu^x (TUC)

19 June 2024; slide 14

Kinetics of microbial growth & modelling


Microbial density


Gas composition

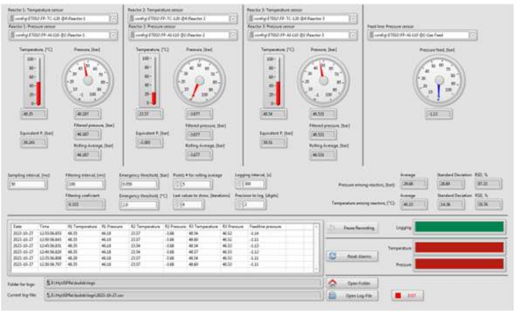

Pressure drop

Kinetics of microbial growth & modelling

What about high pressure?

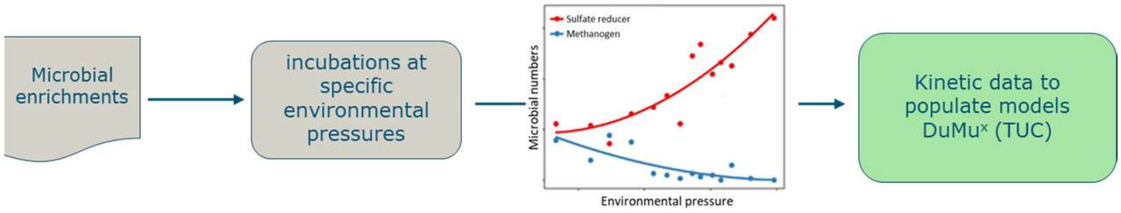
<u>Case 2</u>, Reservoir conditions:
50 ºC
87 bar
pH ~ 6.00
< 50 mg/l sulfate
79 mM acetate

“H_2-only”, 55 bar @$T_{operation}$ of 47±2°C



> 350 days, no H_2 consumption (no sulfide nor methane production)

Competition dynamics between different microbial metabolisms



Microbial enrichments

incubations at specific environmental pressures

Kinetic data to populate models DuMu^x (TUC)

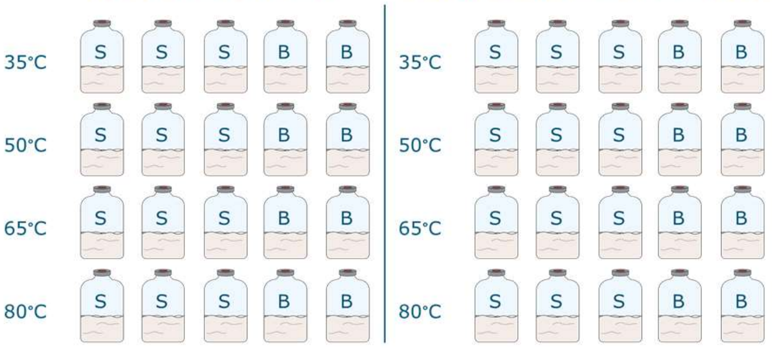
Competition dynamics between different microbial metabolisms

“H_2-only”- samples

100% H_2 + 250 mg/L $NaHCO_3$

“Nutrient-supplemented”-samples

80% H_2/20% CO_2 + 250 mg/L $NaHCO_3$ + nutrients

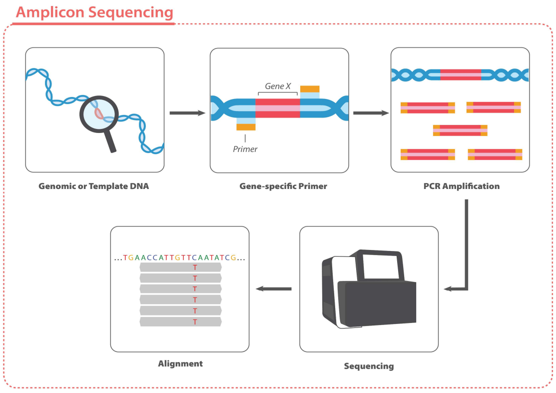


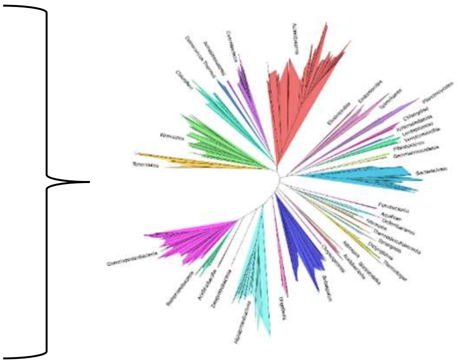
S = Sample, B = Blank

<u>Case 1</u>, Reservoir conditions:
83ºC
116 bar
pH ~ 7.3
0.049 mM sulfate
1 mM acetate

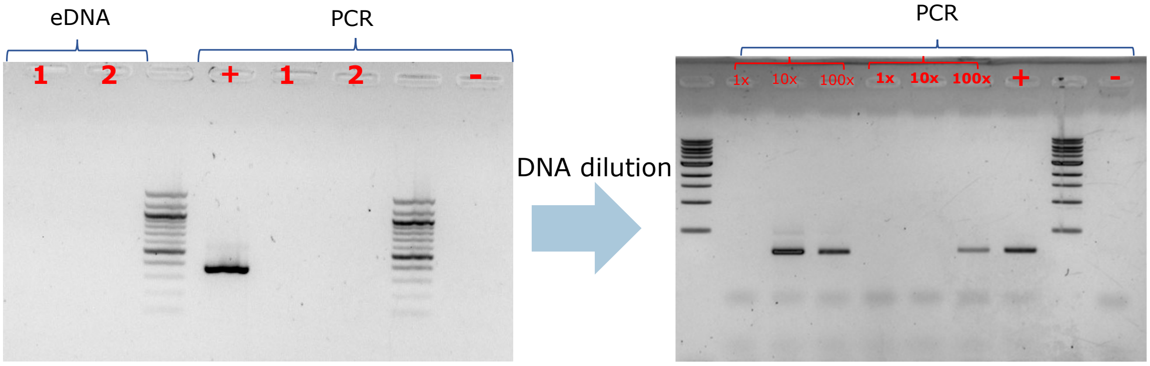
Competition dynamics between different microbial metabolisms

16S rRNA gene-based Microbial Community Analysis

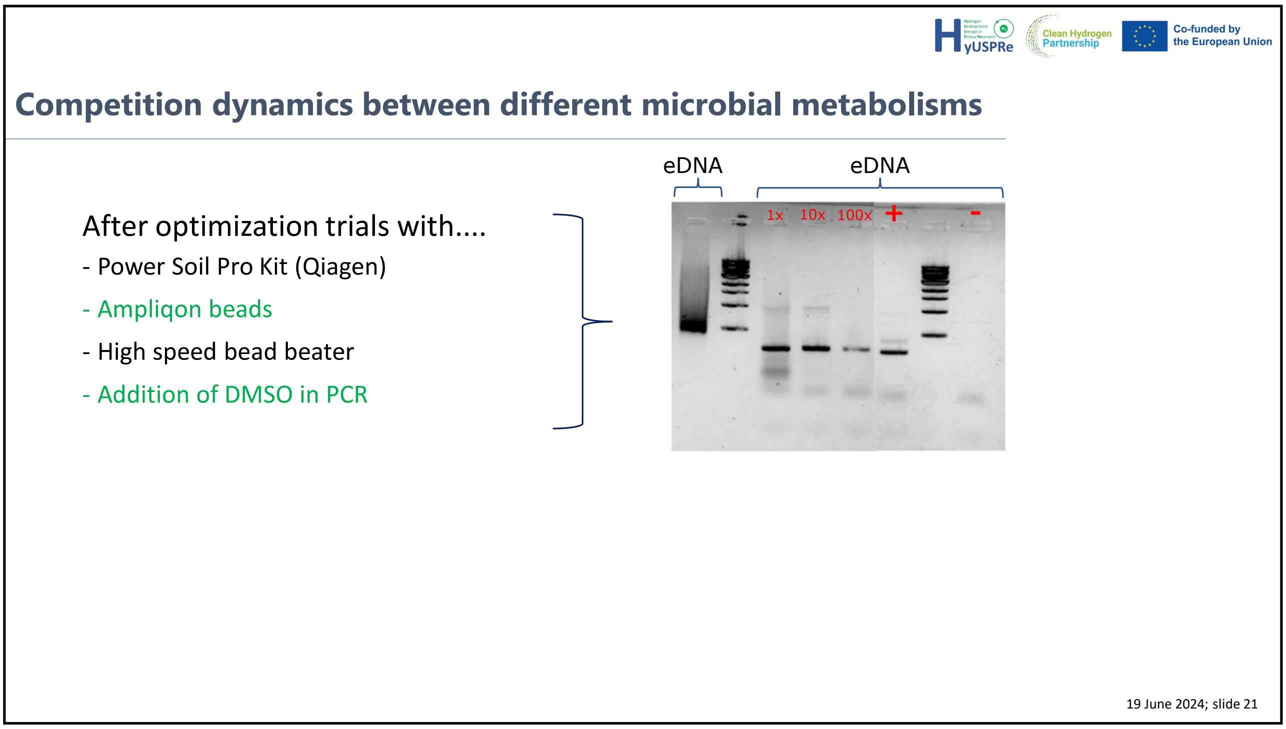




Competition dynamics between different microbial metabolisms



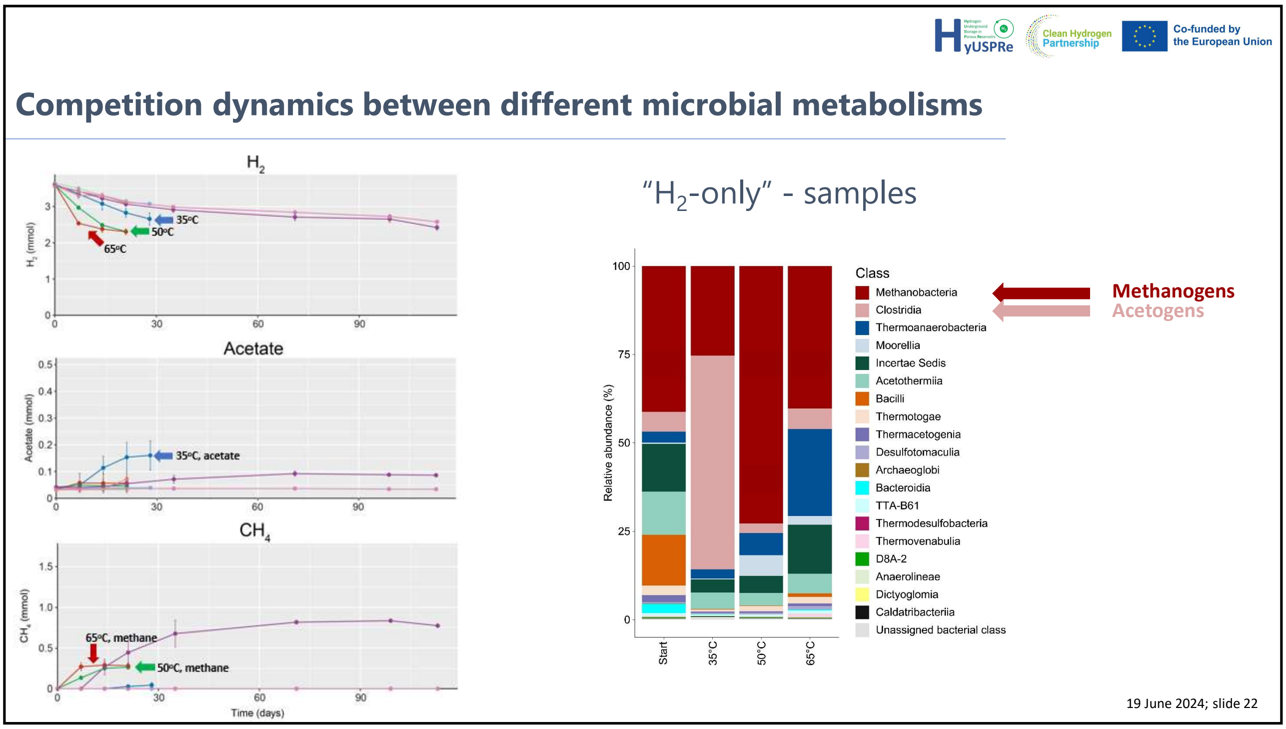
Samples contain very little biomass, but lots of PCR inhibitors...



Competition dynamics between different microbial metabolisms

After optimization trials with....

- Power Soil Pro Kit (Qiagen)
- Ampliqon beads
- High speed bead beater
- Addition of DMSO in PCR

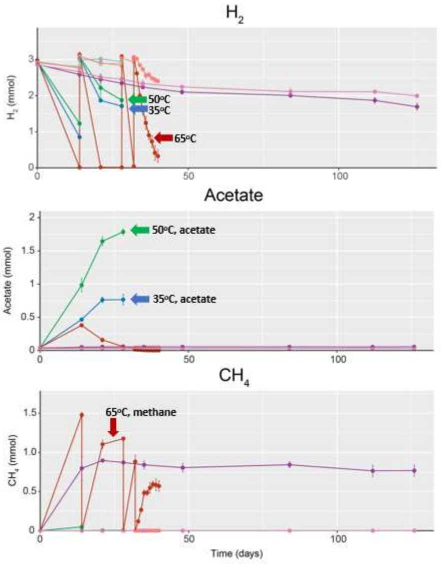


Competition dynamics between different microbial metabolisms

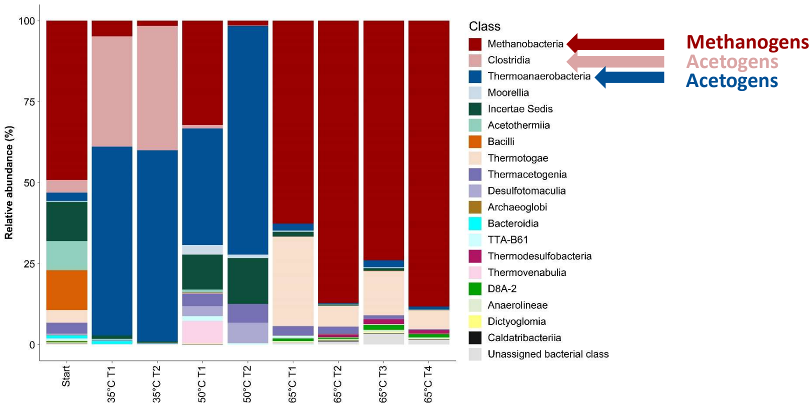
“H_2-only” - samples

Methanogens
Acetogens

Competition dynamics between different microbial metabolisms



“nutrient supplementes” - samples



TAKE HOME MESSAGES WP 3

- **Consumption of H_2 was observed in numerous lab incubations** at low H_2 pressure. Noted incomplete H2 depletion and overall slow process.
- **One site sample tested at high P (55 bar) showed no H_2 depletion.** Further experiments are essential, incorporating diverse samples and conditions for conclusive results.
- Overall, **reduced H_2 depletion was observed at high T** (80 ºC).
- Presence of **sulfate enhances sulfate reducers' activity**, inhibiting other metabolic pathways.
- Chemical composition of the sites, specifically **nutrient availability (P, N, trace elements) should be assessed** as it may condition microbial activity.
- There is a need for optimizing and **harmonizing methods to study microbial activity and diversity in subsurface environments**.

HYUSPRE – FINAL CONFERENCE
19 JUNE 2024 | TNO, UTRECHT

Hydrogen
Underground
Storage in
Porous **Re**servoirs

Co-funded by the European Union

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.

This document reflects the views of the author(s) and does not necessarily reflect the views or policy of the European Commission. Whilst efforts have been made to ensure the accuracy and completeness of this document, the HyUSPRe consortium shall not be liable for any errors or omissions, however caused.

Impact of cyclic hydrogen storage on the reservoir and well system

[10] A real world example: the HyStorage pilot project, Germany (Gion Strobel, Uniper)

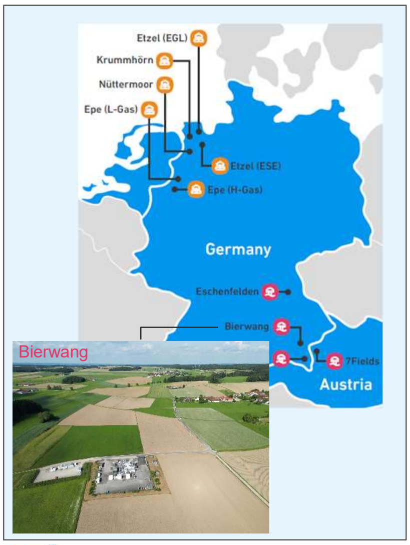
HyStorage Project: Results and Reservoir Modelling

Gion Strobel, Christian Kosack

Agenda

1. Introduction Projects
2. Phase 1 - Overview
3. Phase 1 - Results
4. Phase 1 - Reservoir Modelling
5. Conclusions and Outlook

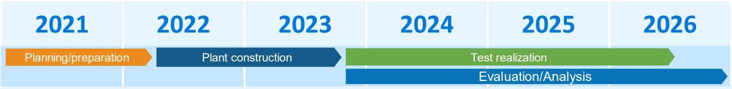
Research project - HyStorage



Effect of H_2 in porous rock

Investigation of the influence of different hydrogen concentrations on porous rock layers.

Timetable



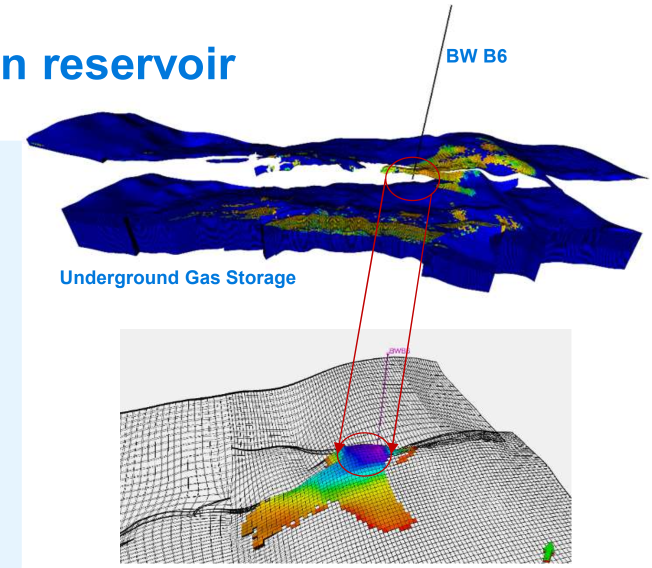
Research Questions

- Is it possible to store hydrogen in a porous rock formation ?
- Which processes are relevant in the operation of large-scale underground hydrogen storages?

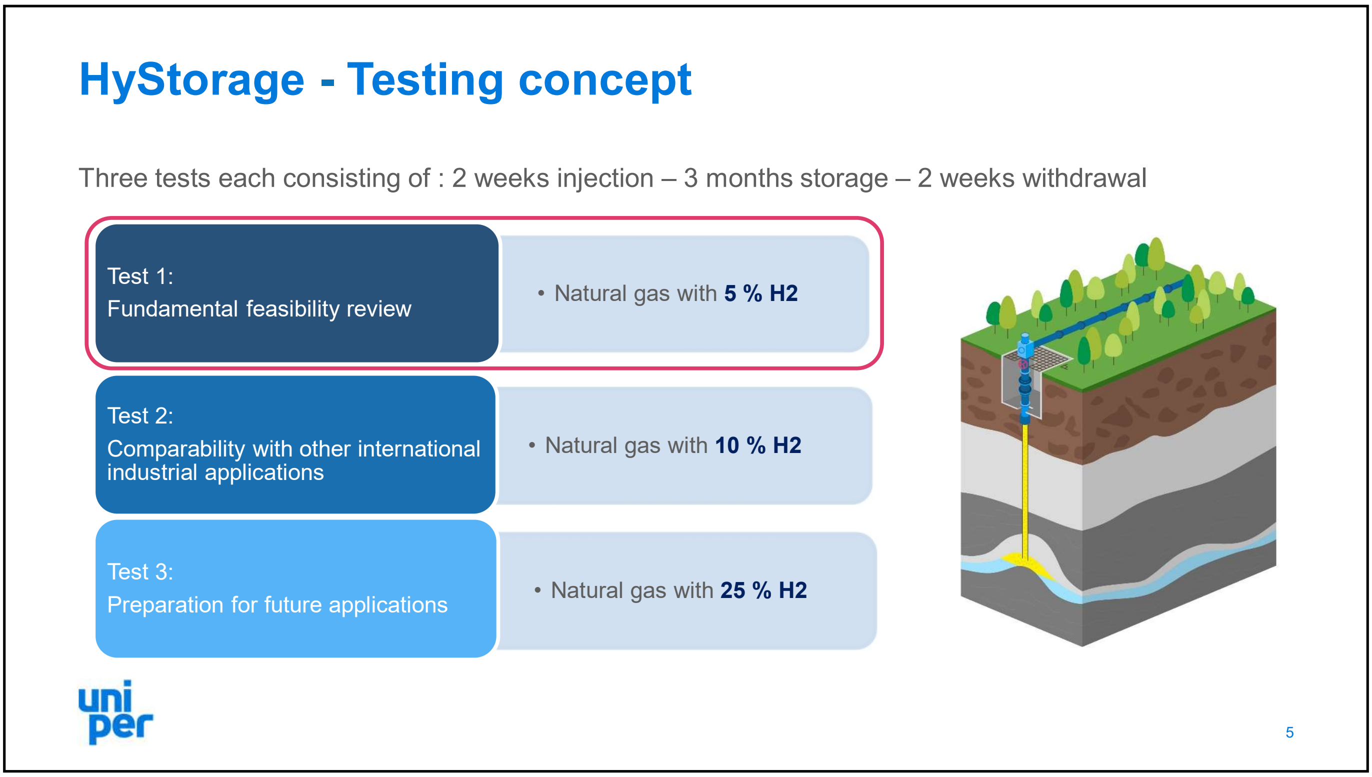
uniper OGE RAG AUSTRIA AG SEFE nafta

Well BW B6 and Aquitanian reservoir

- BW B6 is connected to the Aquitanian reservoir
- Depth of the well: ~1,500 m
- The Aquitanian reservoir is not connected to the storage layers
- No risks to impact the gas storage reservoir
- Transfer results to other porous rock storages of similar lithologies



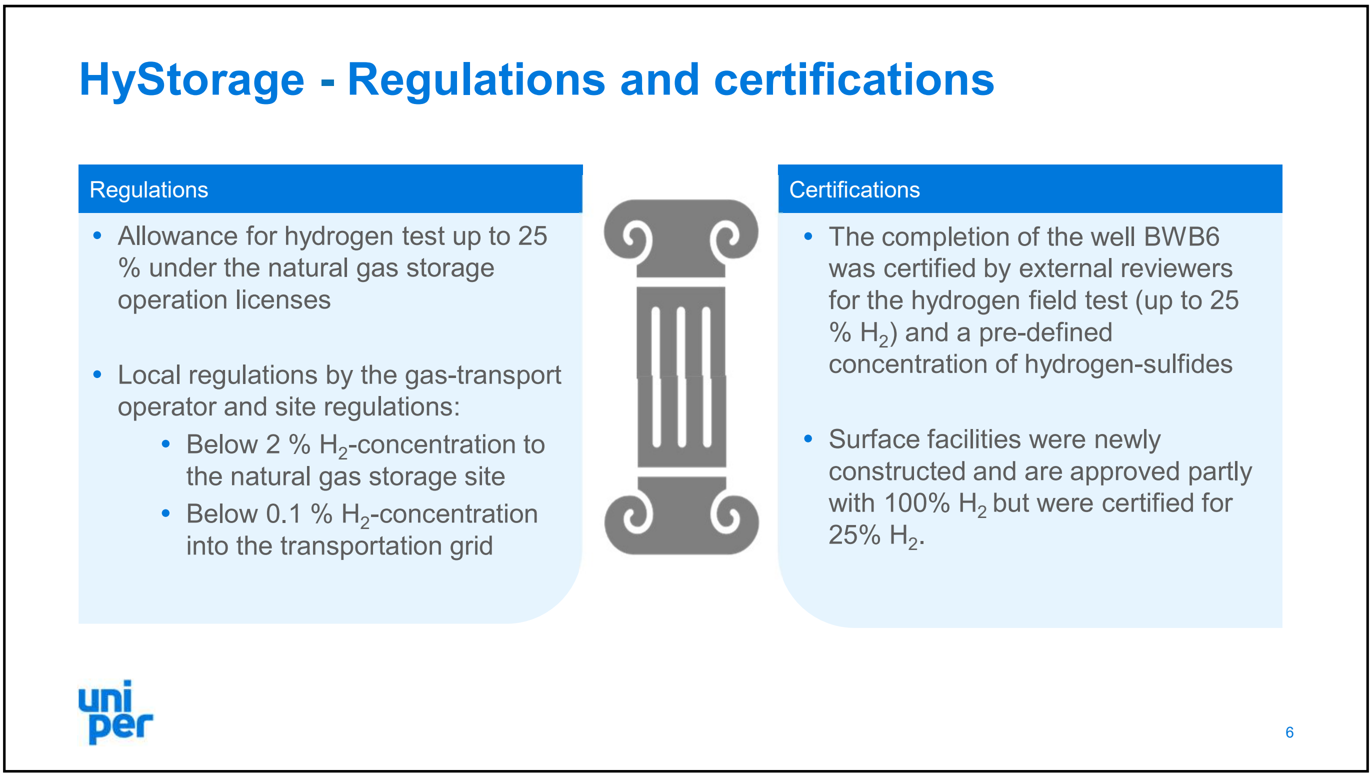
uniper



HyStorage - Testing concept

Three tests each consisting of : 2 weeks injection – 3 months storage – 2 weeks withdrawal

Test 1: Fundamental feasibility review	• Natural gas with **5 % H2**
Test 2: Comparability with other international industrial applications	• Natural gas with **10 % H2**
Test 3: Preparation for future applications	• Natural gas with **25 % H2**



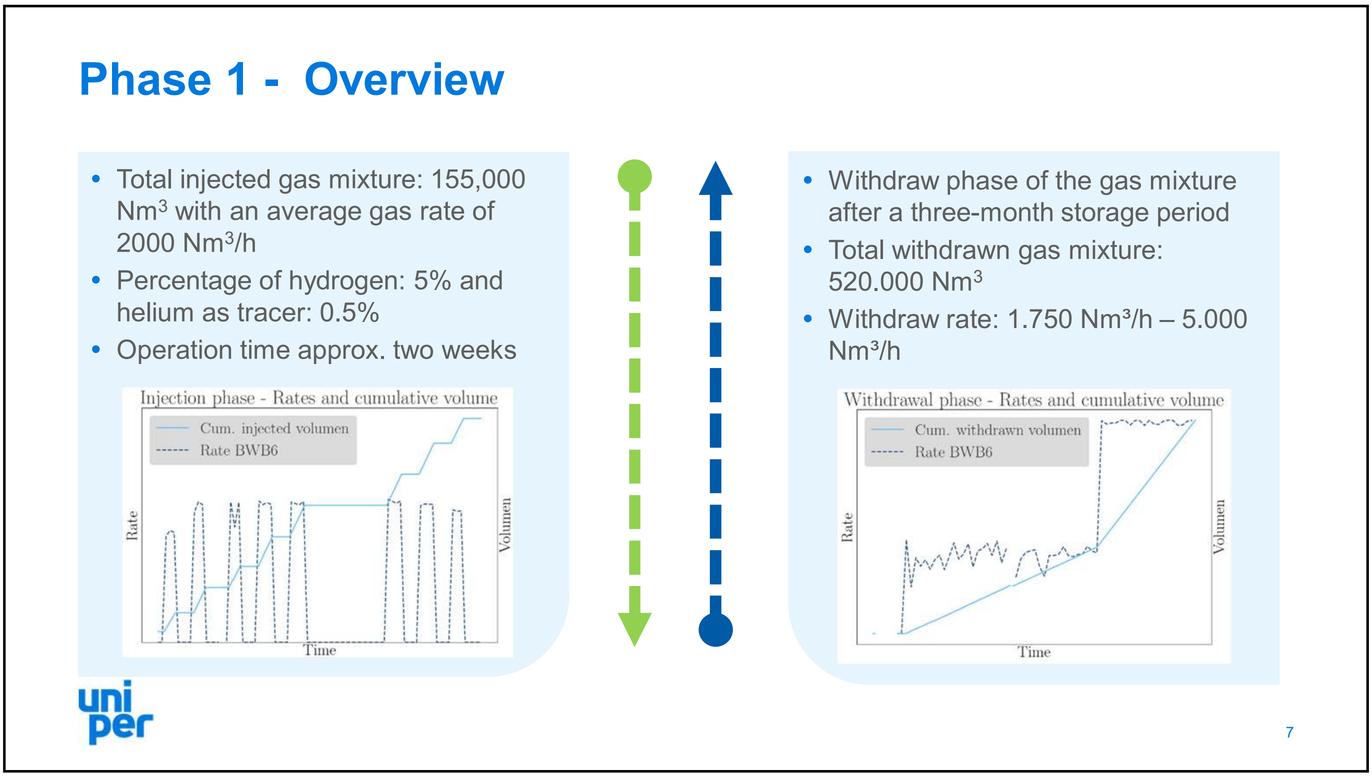
HyStorage - Regulations and certifications

Regulations

- Allowance for hydrogen test up to 25 % under the natural gas storage operation licenses
- Local regulations by the gas-transport operator and site regulations:
  - Below 2 % H_2-concentration to the natural gas storage site
  - Below 0.1 % H_2-concentration into the transportation grid

Certifications

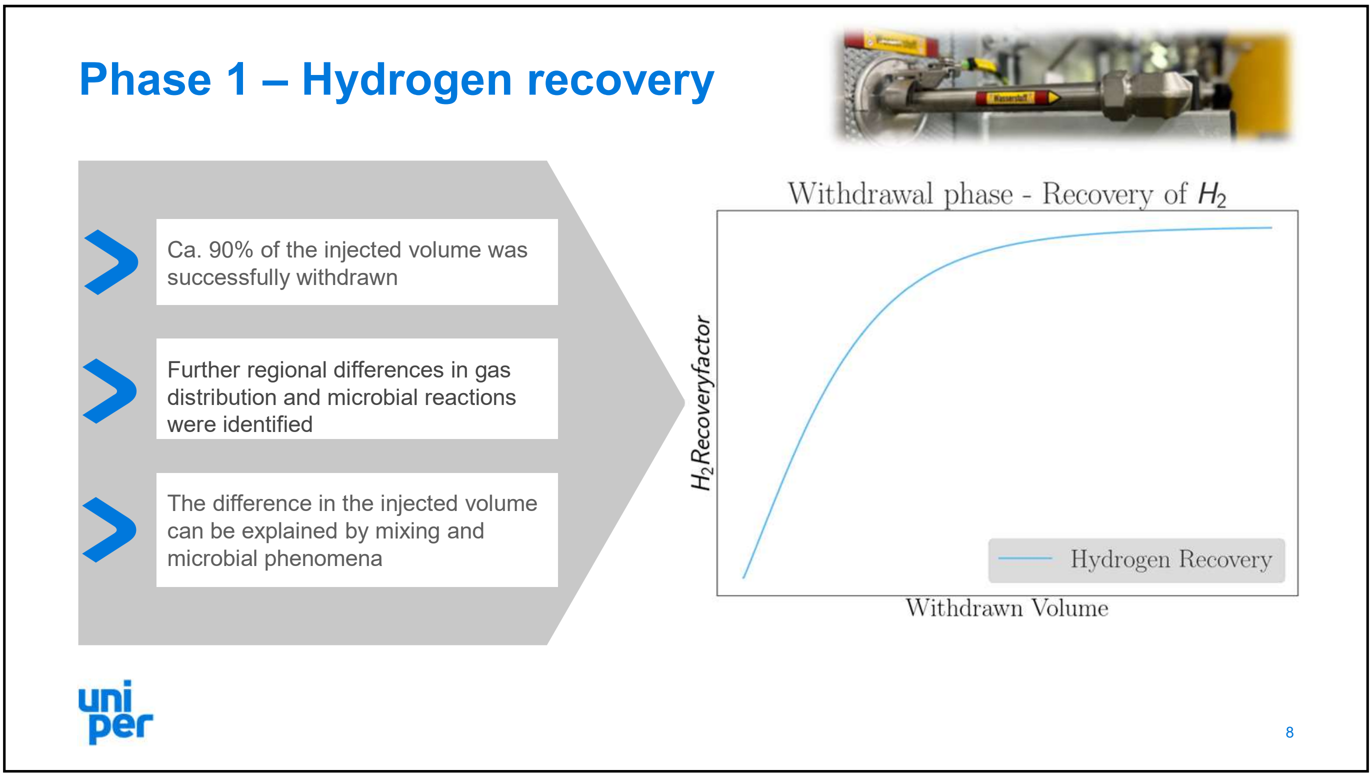
- The completion of the well BWB6 was certified by external reviewers for the hydrogen field test (up to 25 % H_2) and a pre-defined concentration of hydrogen-sulfides
- Surface facilities were newly constructed and are approved partly with 100% H_2 but were certified for 25% H_2.



Phase 1 - Overview

- Total injected gas mixture: 155,000 Nm^3 with an average gas rate of 2000 Nm^3/h
- Percentage of hydrogen: 5% and helium as tracer: 0.5%
- Operation time approx. two weeks

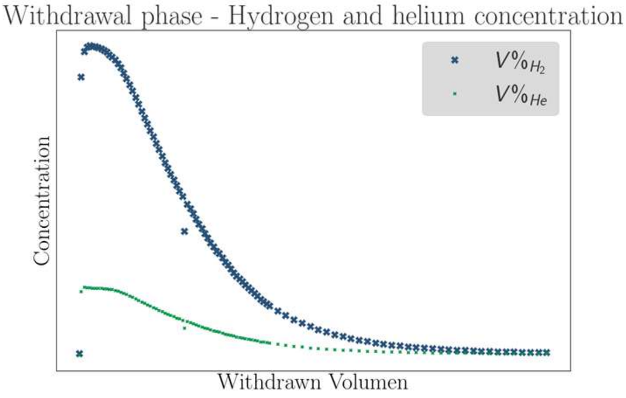
- Withdraw phase of the gas mixture after a three-month storage period
- Total withdrawn gas mixture: 520.000 Nm^3
- Withdraw rate: 1.750 Nm^3/h – 5.000 Nm^3/h

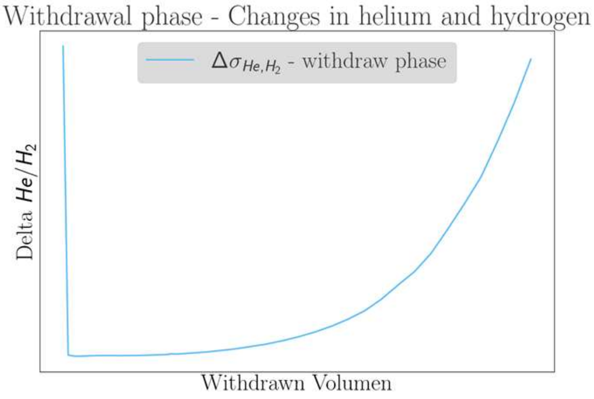


Phase 1 – Hydrogen recovery

- Ca. 90% of the injected volume was successfully withdrawn
- Further regional differences in gas distribution and microbial reactions were identified
- The difference in the injected volume can be explained by mixing and microbial phenomena

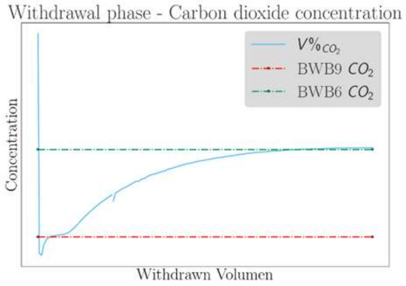
Phase 1 – Results - Mixing phenomena

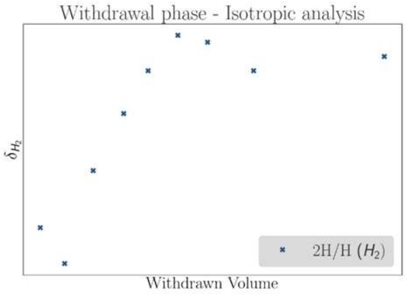




Phase 1 – Results - Microbial effects

Possible microbial effects

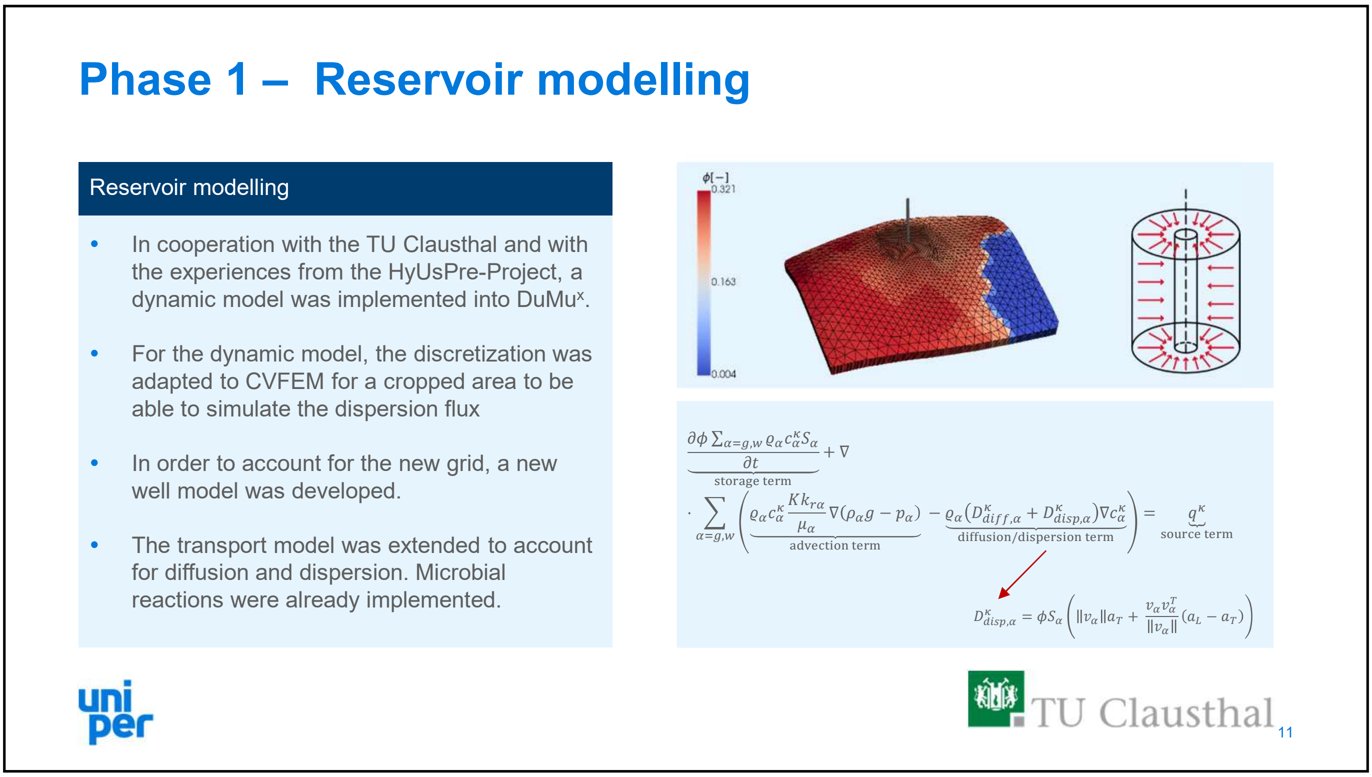




Storage of hydrogen in the reservoir could lead to unfavorable microbial reactions

Observed changes in gas concentrations lead to the assumption of microbial reactions

Complementary isotropic changes support the assumption



Phase 1 – Reservoir modelling

Reservoir modelling

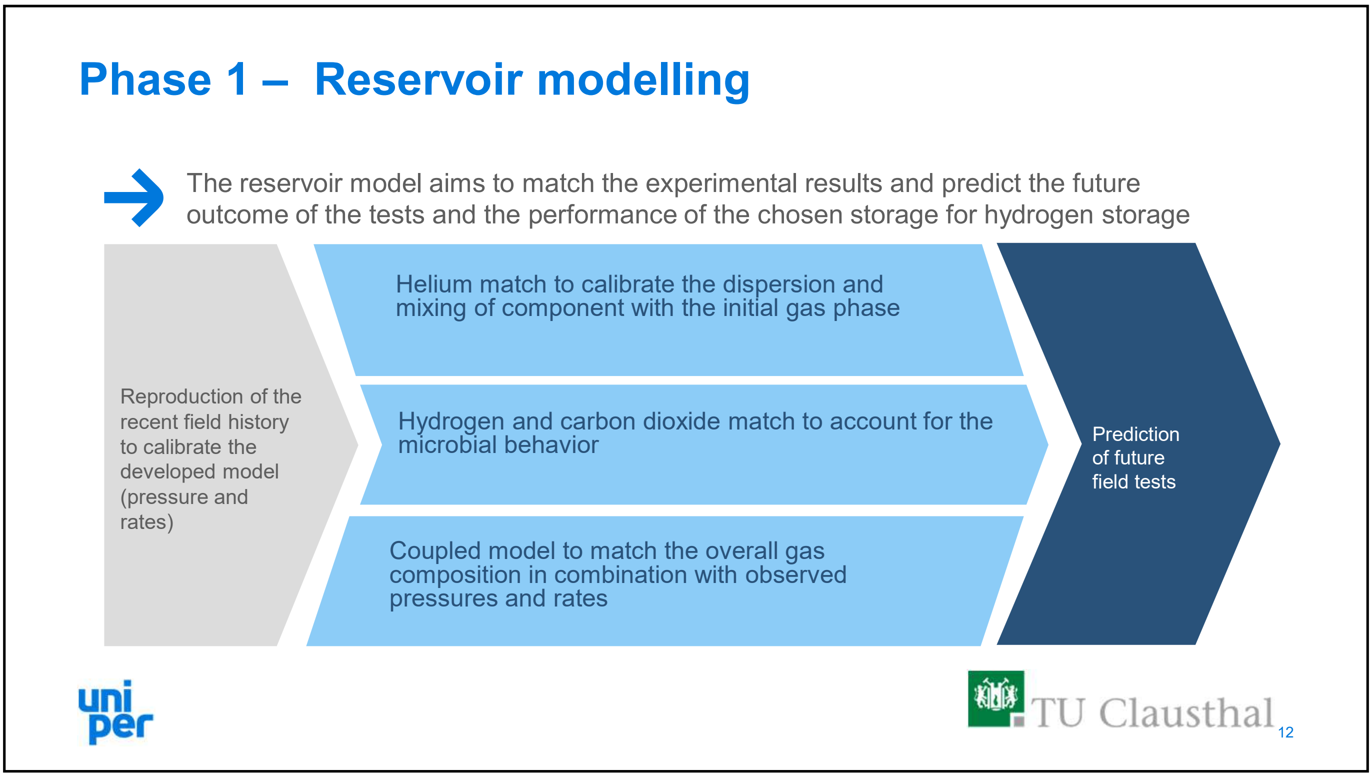
- In cooperation with the TU Clausthal and with the experiences from the HyUsPre-Project, a dynamic model was implemented into DuMu^x.
- For the dynamic model, the discretization was adapted to CVFEM for a cropped area to be able to simulate the dispersion flux
- In order to account for the new grid, a new well model was developed.
- The transport model was extended to account for diffusion and dispersion. Microbial reactions were already implemented.

$$\underbrace{\frac{\partial \phi \sum_{\alpha=g,w} \varrho_\alpha c_\alpha^\kappa S_\alpha}{\partial t}}_{\text{storage term}} + \nabla \cdot \sum_{\alpha=g,w} \left(\underbrace{\varrho_\alpha c_\alpha^\kappa \frac{K k_{r\alpha}}{\mu_\alpha} \nabla(\rho_\alpha g - p_\alpha)}_{\text{advection term}} - \underbrace{\varrho_\alpha \left(D_{diff,\alpha}^\kappa + D_{disp,\alpha}^\kappa\right) \nabla c_\alpha^\kappa}_{\text{diffusion/dispersion term}} \right) = \underbrace{q^\kappa}_{\text{source term}}$$

$$D_{disp,\alpha}^\kappa = \phi S_\alpha \left(\|v_\alpha\| a_T + \frac{v_\alpha v_\alpha^T}{\|v_\alpha\|} (a_L - a_T) \right)$$

uni per

TU Clausthal



Phase 1 – Reservoir modelling

→ The reservoir model aims to match the experimental results and predict the future outcome of the tests and the performance of the chosen storage for hydrogen storage

Reproduction of the recent field history to calibrate the developed model (pressure and rates)

Helium match to calibrate the dispersion and mixing of component with the initial gas phase

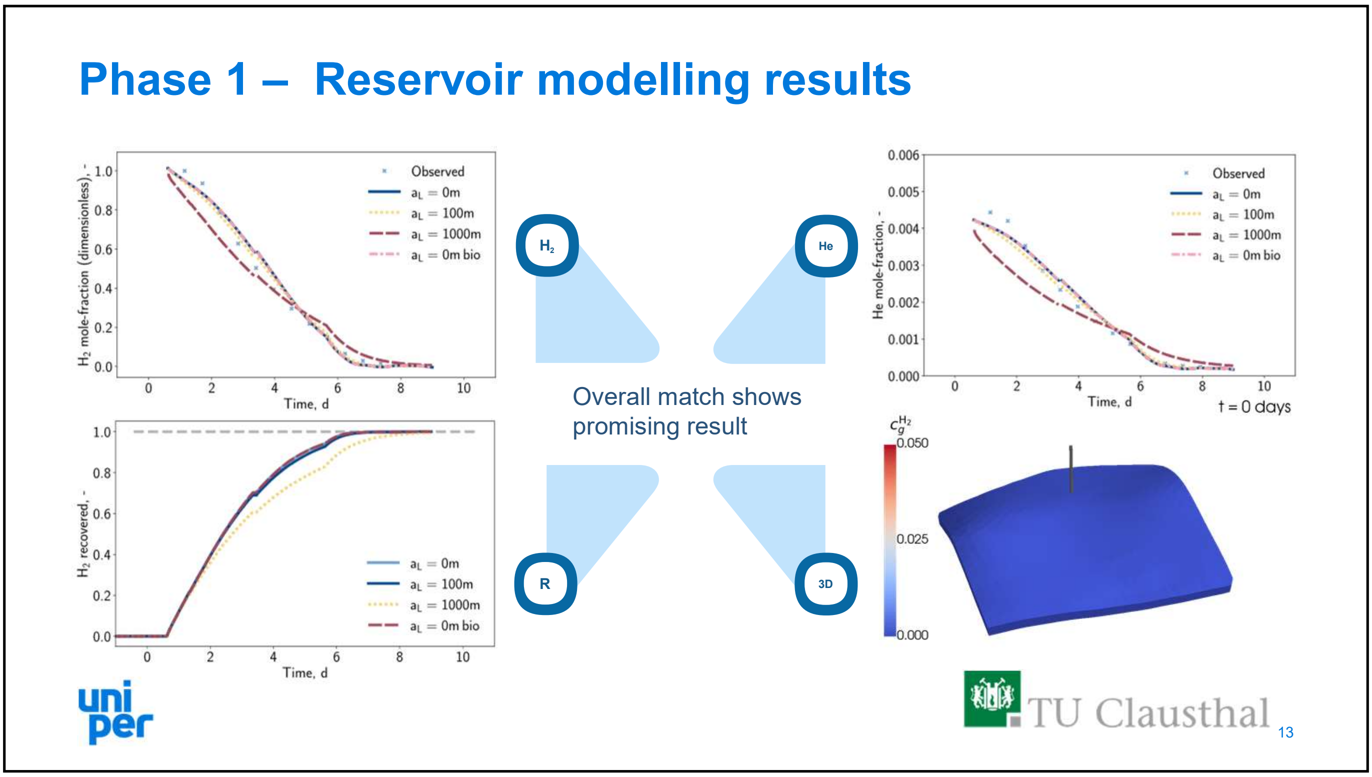
Hydrogen and carbon dioxide match to account for the microbial behavior

Coupled model to match the overall gas composition in combination with observed pressures and rates

Prediction of future field tests

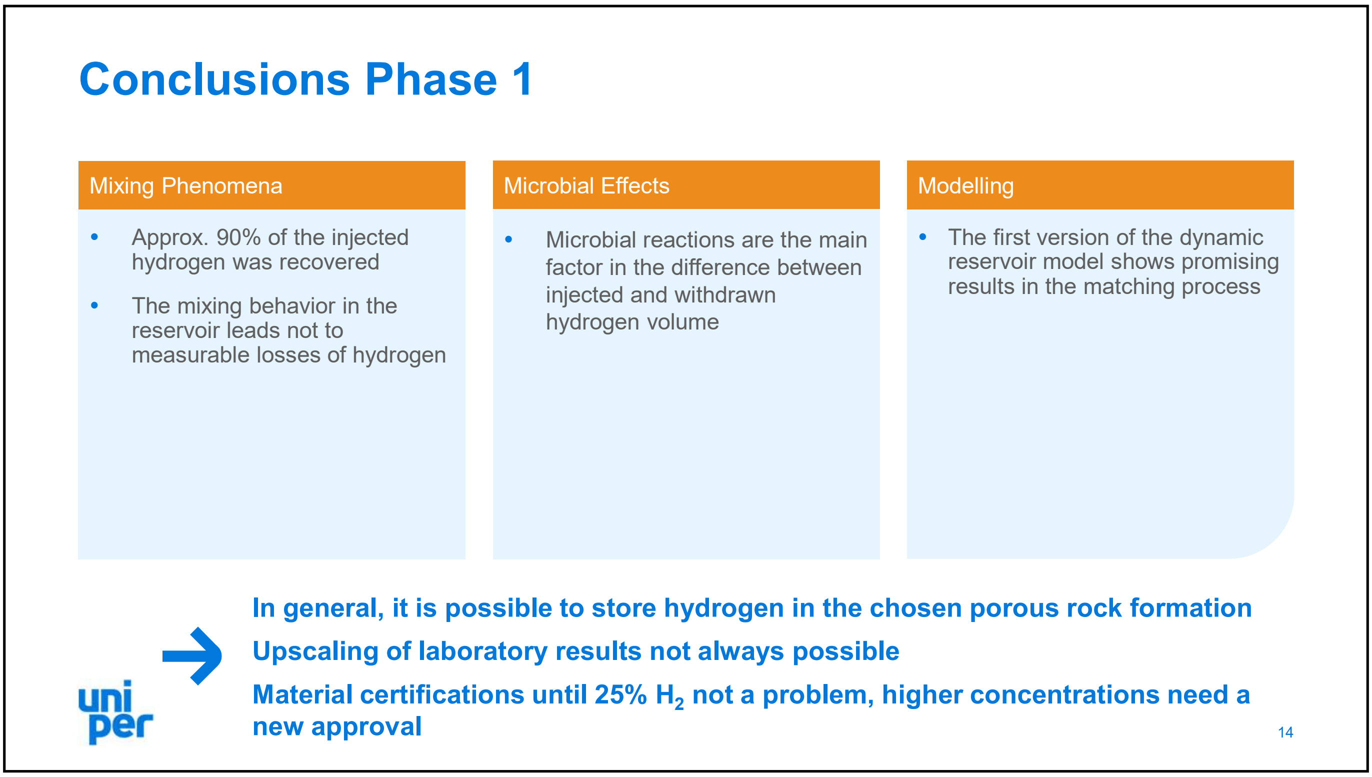
uni per

TU Clausthal



Phase 1 – Reservoir modelling results

Overall match shows promising result



Conclusions Phase 1

Mixing Phenomena

- Approx. 90% of the injected hydrogen was recovered
- The mixing behavior in the reservoir leads not to measurable losses of hydrogen

Microbial Effects

- Microbial reactions are the main factor in the difference between injected and withdrawn hydrogen volume

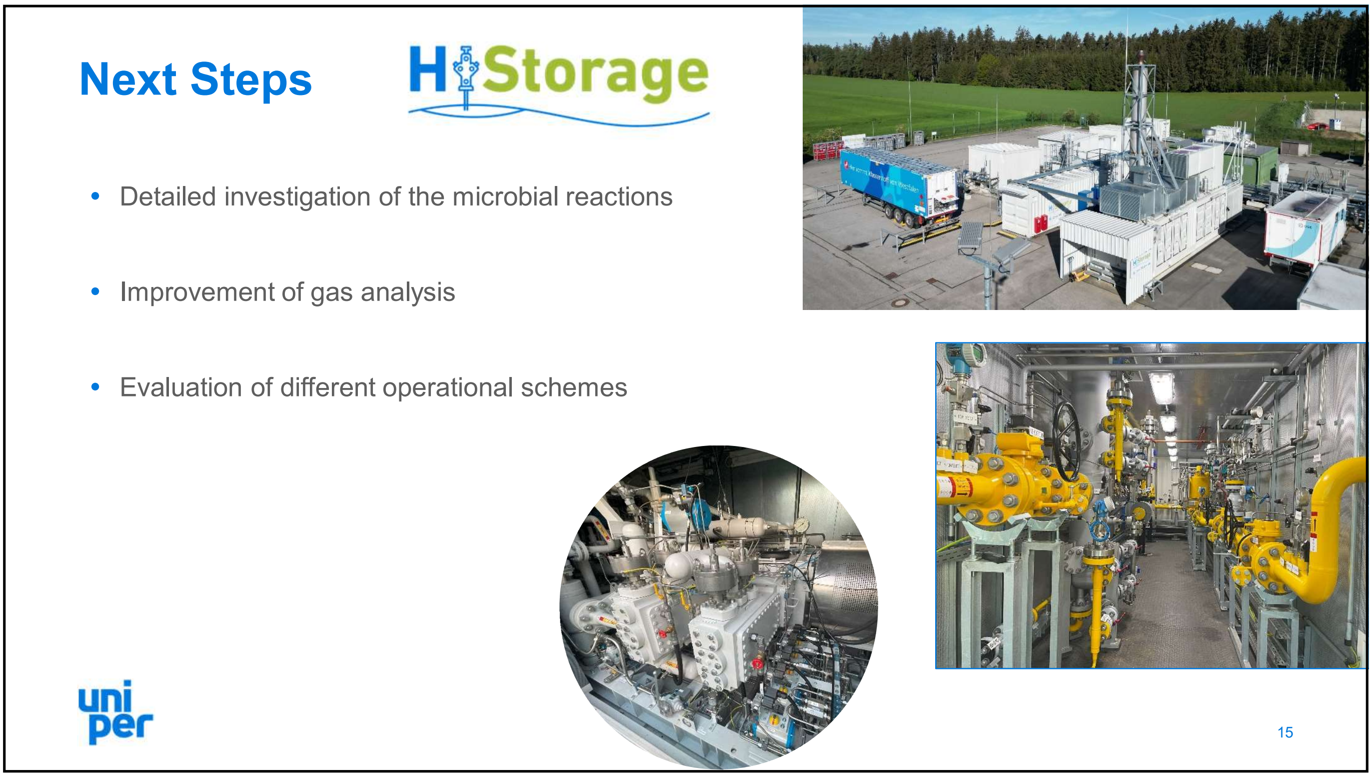
Modelling

- The first version of the dynamic reservoir model shows promising results in the matching process

In general, it is possible to store hydrogen in the chosen porous rock formation

Upscaling of laboratory results not always possible

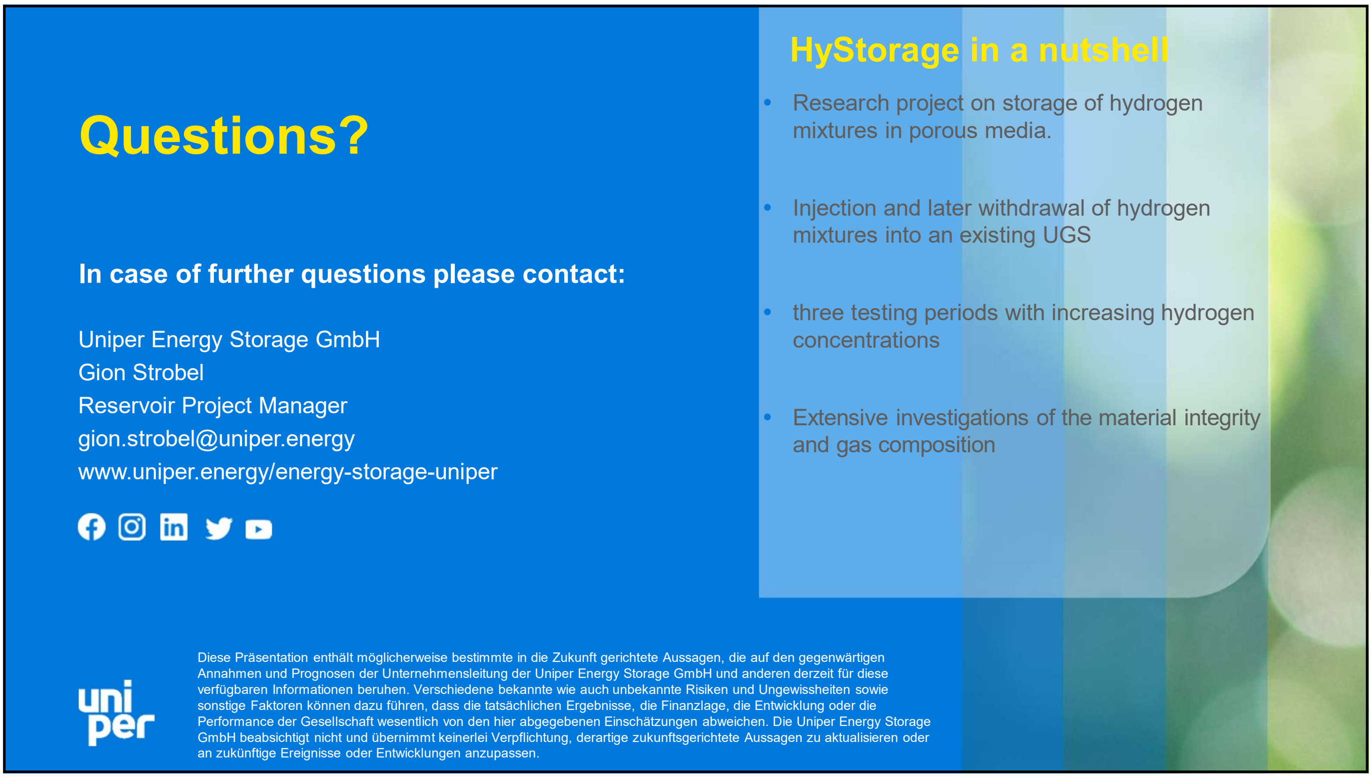
Material certifications until 25% H_2 not a problem, higher concentrations need a new approval



Next Steps

HyStorage

- Detailed investigation of the microbial reactions
- Improvement of gas analysis
- Evaluation of different operational schemes



Questions?

In case of further questions please contact:

Uniper Energy Storage GmbH
Gion Strobel
Reservoir Project Manager
gion.strobel@uniper.energy
www.uniper.energy/energy-storage-uniper

HyStorage in a nutshell

- Research project on storage of hydrogen mixtures in porous media.
- Injection and later withdrawal of hydrogen mixtures into an existing UGS
- three testing periods with increasing hydrogen concentrations
- Extensive investigations of the material integrity and gas composition

Diese Präsentation enthält möglicherweise bestimmte in die Zukunft gerichtete Aussagen, die auf den gegenwärtigen Annahmen und Prognosen der Unternehmensleitung der Uniper Energy Storage GmbH und anderen derzeit für diese verfügbaren Informationen beruhen. Verschiedene bekannte wie auch unbekannte Risiken und Ungewissheiten sowie sonstige Faktoren können dazu führen, dass die tatsächlichen Ergebnisse, die Finanzlage, die Entwicklung oder die Performance der Gesellschaft wesentlich von den hier abgegebenen Einschätzungen abweichen. Die Uniper Energy Storage GmbH beabsichtigt nicht und übernimmt keinerlei Verpflichtung, derartige zukunftsgerichtete Aussagen zu aktualisieren oder an zukünftige Ereignisse oder Entwicklungen anzupassen.

3.2 Poster presentations

Hydrogen production, demand and storage sites

[01] Future hydrogen demand scenarios for Europe (T. Groß & P. Dunkel)

[02] Hydrogen storage potential of existing European gas storage sites in depleted gas fields and aquifers (H. Yousefi et al.)

Geochemical reactions in the storage reservoir

[03] Hydrogen (H_2) trapping and recovery in porous media (E.M. Thaysen et al.)

[04] Microbial risk assessment for underground hydrogen storage in porous rocks (E.M. Thaysen et al.)

[05] Investigating potential for seasonal hydrogen storage within UK offshore hydrocarbon reservoirs and exploiting synergies with offshore wind (A. Peecock et al.)

[06] Risk of H2S generation form the H2 driven reduction of pyrite to pyrrhotite (E. Craenmehr & R. Groenenberg)

Microbiological activity in the storage reservoir

[07] Unveiling microbial dynamics in subsurface H2 storage environment (part 1): a kinetic study (A.C. Ahn et al.)

[08] Unveiling microbial dynamics in subsurface H2 storage environment (part 2): a competition study (A.C. Ahn et al.)

Hydrogen reservoir flow behavior

[09] Experimental Investigations of Molecular Diffusion and Mechanical Dispersion during UHS (J. Michelsen et al.)

Durability and integrity of well and rock materials

[10] Impact of cyclic hydrogen storage on porous reservoirs' flow and mechanical properties (V. Soustelle et al.)

[11] Microbial influenced corrosion and potential impact of H2 on subsurface storage processing facility elements (J. Dykstra et al.)

Integrative multi-scale modelling and guidance for suitability assessment

[12] Numerical Simulation of Bio-Geo-Reactive Transport during UHS - A Modelling Approach (S. Hogeweg et al.)

[13] Guidelines for reservoir and site suitability assessments in hydrogen storage: advancing from TRL 4 to in-field demonstration at TRL 5 (F. Farajimoghadam et al.)

[14] Numerical modeling of bio-reactive transport during underground hydrogen storage – A benchmark study (N. Khoshnevis Gargar et al.)

[15] Well integrity and leakage analysis for a hydrogen storage well (A. Moghadam et al.)

Techno-economic assessment of EU scenarios for hydrogen storage

[16] Underground storage in EU scale hydrogen system scenarios (T. Groß & P. Dunkel)

[17] Stakeholder analysis of underground hydrogen storage (D. Markova et al.)

Hydrogen production, demand and storage sites

[01] Future hydrogen demand scenarios for Europe (T. Groß & P. Dunkel)

Future Hydrogen Demand Scenarios for Europe

1. Introduction

Hydrogen is a pivotal technology for achieving the EU's Green Deal goals of greenhouse gas neutrality by 2050, as emphasized by the European Commission.

Key Benefits of Hydrogen:

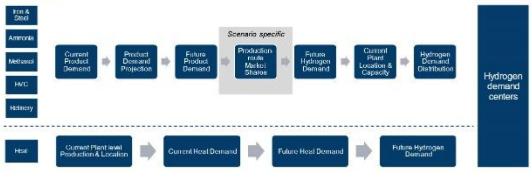
- **Industry Sector**: Hydrogen brings the opportunity to decarbonize carbon intensive industrial processes.
- **Transport Sector**: It provides a viable alternative for decarbonizing heavy-duty transport, aviation, and maritime sectors, where electrification is challenging.
- **Energy Storage**: Hydrogen storage can balance the future renewable energy-based electricity system.

This work estimates the **future hydrogen demand** and identifies potential **demand centers** across Europe by 2050, due to the utilization of hydrogen in the industry and transport sector.

2. Methodology

For **industry**, hydrogen as **feedstock** and fuel for **high-temperature process heat** are identified as main applications. In the **transport** sector, hydrogen is assumed to be used within **FCEV** and **feedstock for synthetic fuels**. Road, maritime, aviation and rail transport are considered. **Three scenarios** are created: *reduced, baseline, ambitious* considering **different hydrogen penetrations**. Hydrogen demands are derived at *regional* level.

Industry



Iron & Steel
Ammonia
Methanol
HVC
Refinery

Current Product Demand → Product Demand Projection → Future Product Demand → Production route Market Shares → Future Hydrogen Demand → Current Plant Location & Capacity → Hydrogen Demand Distribution

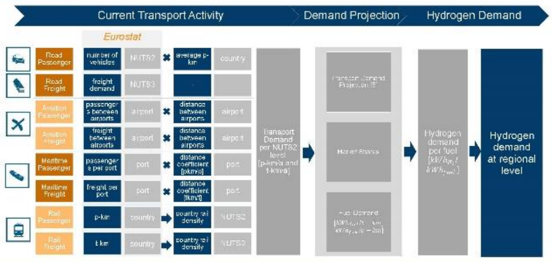
Scenario specific

Heat

Current Plant level Production & Location → Current Heat Demand → Future Heat Demand → Future Hydrogen Demand

Hydrogen demand centers

Transport



Current Transport Activity | Demand Projection | Hydrogen Demand

Eurostat

Road Passenger	number of vehicles	NUTS2	✖	average p-km	country
Road Freight	freight demand	NUTS3			
Aviation Passenger	passengers between airports	airport	✖	distance between airports	airport
Aviation Freight	freight between airports	airport	✖	distance between airports	airport
Maritime Passenger	passengers per port	port	✖	distance coefficient [pkm/p]	port
Maritime Freight	freight per port	port	✖	distance coefficient [tkm/t]	port
Rail Passenger	p-km	country	→	country rail density	NUTS2
Rail Freight	t-km	country	→	country rail density	NUTS2

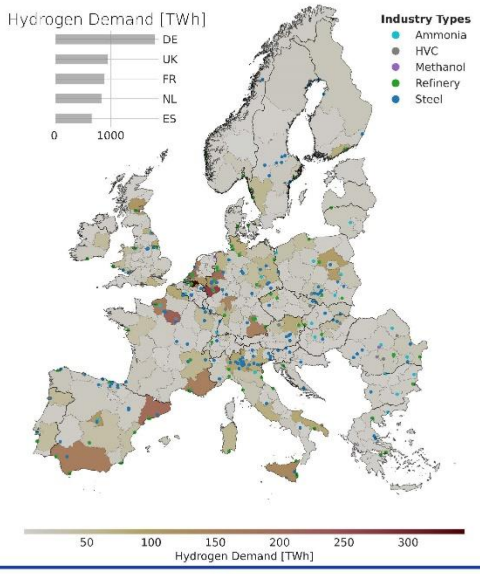
Transport Demand per NUTS2 level [p-km/a and t-km/a] → Transport Demand Projection [%] / Market Shares / Fuel Demand → Hydrogen demand per fuel → Hydrogen demand at regional level

3. Results

Future Hydrogen Demand Projections (2050):

- **Range**: 3100-5000 TWh across three demand scenarios (reduced, baseline, ambitious).
- **Industry**: High-value chemicals (HVC) production leads the demand, potentially exceeding 1400 TWh.
- **Transport**: Demand could reach 1900 TWh, with passenger aviation and road freight as major contributors.

Geographical Distribution: Potential hydrogen demand centres are located in today's industrial centres in Europe as well as in places with high transportation needs, such as airports and ports.



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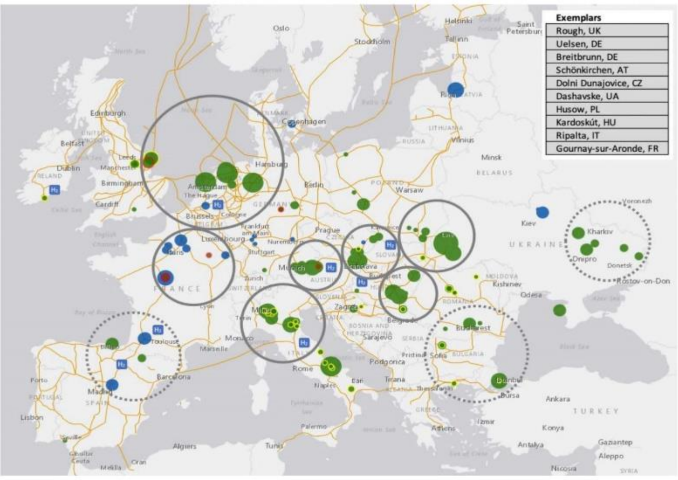
Hydrogen production, demand and storage sites

[02] Hydrogen storage potential of existing European gas storage sites in depleted gas fields and aquifers (H. Yousefi et al.)

HYDROGEN STORAGE POTENTIAL OF EXISTING EUROPEAN GAS STORAGE SITES IN DEPLETED GAS FIELDS AND AQUIFERS

Storage capacity estimation

- **320-415 TWh** H_2 storage potential in porous reservoirs in Europe currently used for storing natural gas: **15-18%** of demand for a mid-range scenario of 2,500 TWh of annual H_2 demand in 2050.
- Uncertain: **fraction** and **timing** of conversion of UGS in porous reservoirs to hydrogen storage.

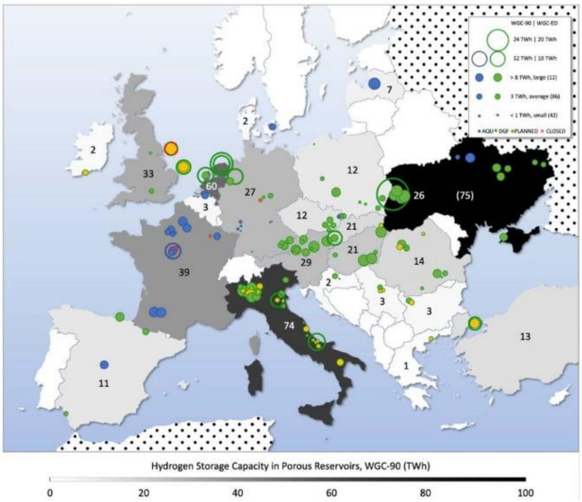


Gap analysis

- Capacity gap ranges from **250-1,000 TWh** depending on H_2 demand and level (fraction, timing) of conversion of UGS sites.
- 1,000 TWh gap (high H_2 demand) requires **400 storage sites**, whereas a 250-500 TWh gap (low-to-mid H_2 demand) needs 100-200 storage sites.

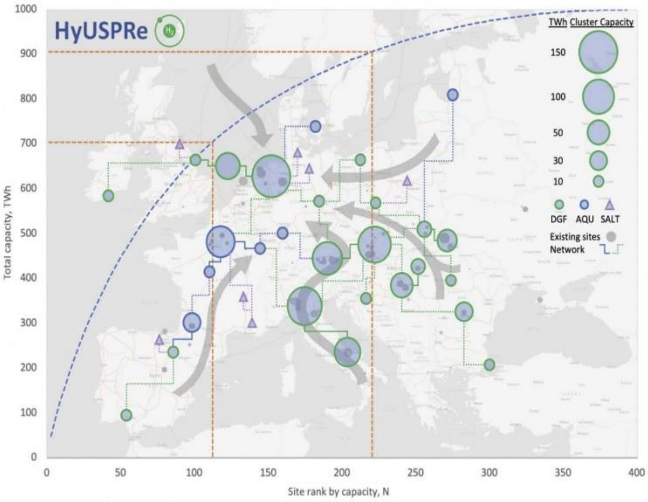
Methodology

- Storage capacity in existing UGS estimated using **static** (0.25) and **rate-limited** (0.3-0.5) conversion factors.
- Higher rates for H_2 due to **lower viscosity and density** relative to methane compensate for lower energy density of H_2 vs. methane.



Cluster analysis

- Determining **seven clusters** based on reservoir type, working pressure window, temperature, and permeability.
- Identifying a shortlist of **exemplars** (10) and **prototypes** (10) for targeting new sites to increase the reserve.



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Use QR code to access the ***HyUSPRe atlas of hydrogen storage potential in porous reservoirs in Europe***

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Hydrogen Underground Storage in Porous Reservoirs HyUSPRe

Clean Hydrogen Partnership

Co-funded by the European Union

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Geochemical reactions in the storage reservoir

[03] Hydrogen (H_2) trapping and recovery in porous media (E.M. Thaysen et al.)

Hydrogen (H_2) trapping and recovery in porous media

Eike M. Thaysen[1], Katriona Edlmann[1], Ian B. Butler[1]

[1]The University of Edinburgh, School of Geosciences, The King's Buildings, James Hutton Road, EH9 3FE Edinburgh, UK

The problem

Subsurface storage of H_2 in geological porous media is a large-scale and economic means to overcome imbalances between supply and demand in renewable energy. Mechanisms related to H_2 flow and capillary trapping have not been investigated, yet such data are vital to predict H_2 plume development and to define recovery strategies.

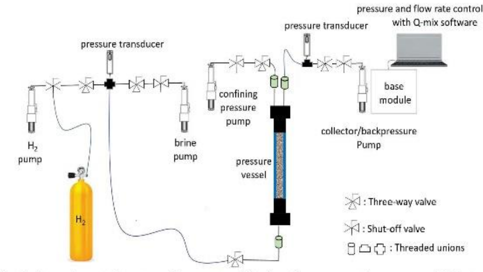

Fig.1: Experimental setup. The materials for the connections were 316 stainless steel (black), HPLC (green) and PEEK or carbon fibre reinforced PEEK (blue).

Methods

- Non-steady state, cyclic H_2 and brine flow experiments conducted at 2-7 MPa and 20-80 µl min^{-1} in Clashach sandstone cores (4.7 mm OD x 53-57 mm)
- Two phase fluid distributions after primary drainage and secondary imbibition were imaged using X-ray microtomography (Fig. 1)
- Nitrogen (N_2) and H_2 were compared since N_2 can be used as an experimental analogue for H_2

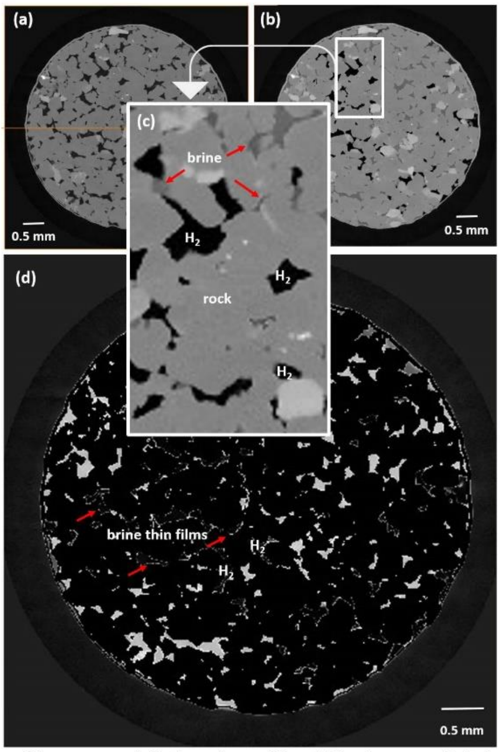

Fig.2: (a) Water-wet Clashach sandstone. (b) and (c) Brine-saturated Clashach sandstone after injection of H_2. (d) Subtraction of the water-wet scan from the brine-saturated scan after H_2 injection revealing brine thin films around grains.

Headlines

- H_2 displacement processes in porous rock were imaged as a function of pore fluid pressure and capillary number.
- Results showed no clear relation between the H_2 saturation during drainage and pore fluid pressure.
- Capillary trapping of H_2 during brine imbibition at 2, 5 and 7 MPa and a capillary number of 2.4×10^{-6} accounted for 20%, 24% and 43% of the initial H_2 trapped, respectively, indicating that higher pressure, i.e. deeper reservoirs are less favourable for H_2 storage.

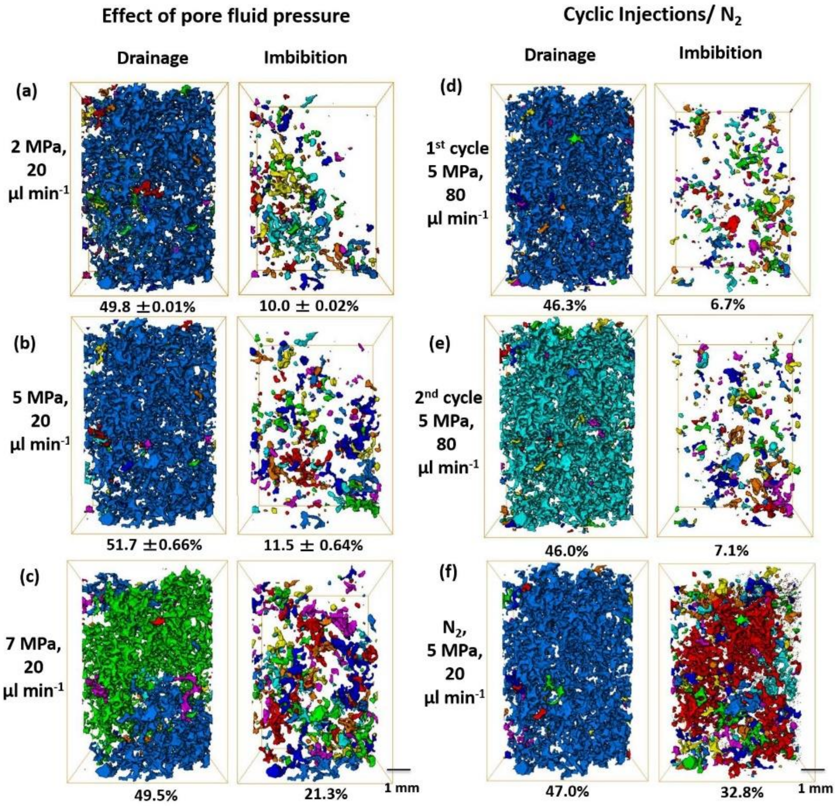

Fig.3: (a-c) Effect of pore fluid pressure on H_2 clusters and saturation after drainage and after imbibition. (a) 2 MPa, (b) 5 MPa and (c) 7 MPa, all at a flow rate of 20 µl min^{-1} (capillary numbers of 1.7×10^{-8} and 2.4×10^{-6} for H_2 and brine, respectively). (d-e) Effect of cyclic injections on H_2 clusters and saturation: (d) Primary drainage and imbibition and (e) secondary drainage and imbibition, all at 5 MPa and a flowrate of 80 µl min^{-1} (capillary number of 9.4×10^{-6}). f) N_2 clusters and saturations during drainage and imbibition at 5 MPa and a flowrate of 20 µl min^{-1}.

Results

- H_2 behaved as a non-wetting phase and sat in the centre of the pores (Fig. 2b,c)
- Residual brine sat in corners, pore throats and in thin films around grains (Fig. 2b,c,d)
- H_2 saturation during drainage was ~50% of the PV regardless of pore fluid pressure (Fig. 3a-c)
- Secondary drainage and imbibition did not affect the H_2 saturation (Fig. 3d, e)
- H_2 saturation during drainage and imbibition decreased with increased flow rate (Fig. 3b,e)
- Capillary trapping of H_2 accounted for 20%, 24% and 43% of the initial H_2 trapped at 2, 5 and 7 MPa, respectively (Fig. 3a-c)
- N_2 behaved like H_2 during drainage but N_2 saturation after imbibition was much higher (32.8% vs. 11.5%; Fig. 3 f,b). N_2 is hence not suitable for use as a proxy for H_2

Hydrogen Underground Storage in Porous Reservoirs HyUSPRe

Clean Hydrogen Partnership

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Geochemical reactions in the storage reservoir

[04] Microbial risk assessment for underground hydrogen storage in porous rocks (E.M. Thaysen et al.)

Microbial risk assessment for underground hydrogen storage in porous rocks

Eike Marie Thaysen[1], Tim Armitage[1], Lubica Slabon[1], Aliakbar Hassanpouryouzband[1], Katriona Edlmann[1]

[1]The University of Edinburgh, School of Geosciences, The King's Buildings, James Hutton Road, EH9 3FE Edinburgh, UK

1. THE PROBLEM

Subsurface storage of hydrogen (H_2) in geological porous media is a large-scale and economic means to overcome imbalances between supply and demand in the renewable energy sector. A range of subsurface microbes utilise H_2, which may have important implications for H_2 recovery, clogging and corrosion.

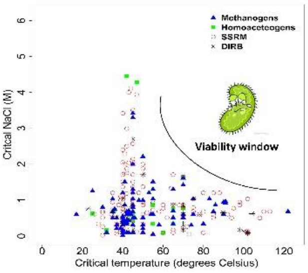

Fig.1: Critical temperature versus critical salinity for major H_2-utilizing microbes (Thaysen et al. in review).

2. METHODS

- We created a novel, globally applicable risk categorization tool based on the growth constraints of all major H_2-utilizing microbes (Fig. 1).
- We gathered temperature and salinity data for 75 depleted gas fields on the UK continental shelf and GIS-mapped their risk of adverse microbial effects (Fig. 2)
- Results were aligned with centres for renewable energy production (Fig. 3) and out-of-use pipelines suitable for repurposing to transport H_2 (Fig. 4)

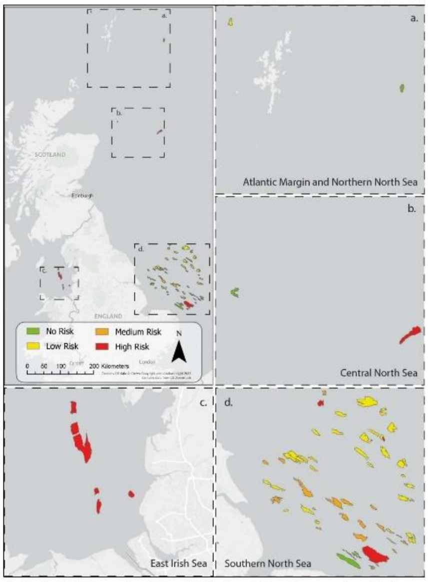

Fig. 2: Microbial risk categorization for 75 depleted gas fields on the UK continental shelf.

3. RESULTS

- We recommend storing H_2 in 9 depleted gas fields that are at no risk due to temperatures >122 °C, or in the 35 low-risk depleted gas fields >90 °C.
- We recommend against using high-risk depleted gas fields <55°C (9 fields).
- No Risk or Low Risk depleted gas fields in the Southern North Sea are most suitable for H_2 storage.

No risk

Fields ≥ 122 °C can be considered sterile (Fig. 1).

Low risk

Fields > 90 °C can be considered paleosterile (based on oil field reports).

Medium risk

Cultivated microbes cannot grow at ≥55 °C and salinities >1.7 M NaCl (Fig. 1), yet, non-cultivated microbes may be able to.

High risk

Fields <55 °C, where the majority of H_2-utilizing microbes show optimum growth and where extreme salinity tolerance is found (Fig. 1).

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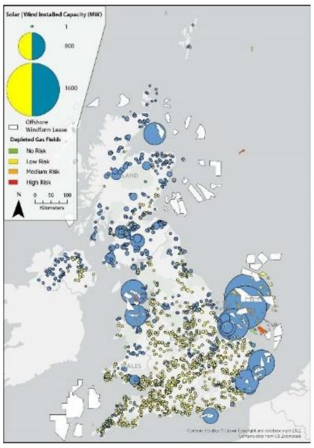

Fig. 3. Installed solar and wind capacity in the UK overlain with offshore wind licenses and the microbial risk categorization for 75 depleted gas fields on the UK continental shelf.

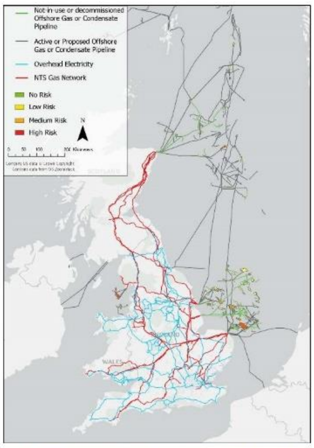

Fig. 4: Offshore gas and condensate pipeline infrastructure overlain by the microbial risk categorization for 75 depleted gas fields. Onshore, overhead electricity network for England and Wales and the onshore gas National Transmission System for Britain.

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Geochemical reactions in the storage reservoir

[05] Investigating potential for seasonal hydrogen storage within UK offshore hydrocarbon reservoirs and exploiting synergies with offshore wind (A. Peecock et al.)

Investigating potential for seasonal hydrogen storage within UK offshore hydrocarbon reservoirs and exploiting synergies with offshore wind

Anna Peecock, Katriona Edlmann, Julien Mouli-Castillo, Alfonso Martinez-Felipe & Russell McKenna

Based on research presented in Peecock, A., et al. (2023). "Mapping hydrogen storage capacities of UK offshore hydrocarbon fields and investigating potential synergies with offshore wind." Geological Society, London, Special Publications **528**(1): SP528-2022-2040.

1. Background

- Long-term energy storage at scale provides a mechanism to flexibly transfer energy across sectors, time and space, and will be a keystone for successful energy system integration.
- Excess renewable electricity generation can power electrolysers in times of peak supply; the generated green hydrogen (H_2) can then be applied in times of short supply and higher demand in different sectors.
- The coupling of green H_2 production and geological storage may therefore be an efficient balancing mechanism to support seasonal variation in demand in net-zero economies.[1]
- Storing H_2 in depleted fields offers the opportunity to repurpose existing infrastructure, widespread geographic availability, and reduced cushion gas requirements, decreasing installation costs.
- Despite its greater diffusivity, compressibility factor and lower viscosity, hydrogen losses through dissolution and diffusion through the caprock are negligible. [2]
- Until a commercial site is developed, it remains to be seen whether technical challenges, including geochemical reactions and microbial activity within the reservoirs, can be overcome and their associated risks managed.

2. Methods & Results

Hydrogen storage demand estimate:

Quantify domestic natural gas demand and estimate inter-seasonal storage needs

Determine amount of hydrogen required to meet demand, in both 20% and 100% conversion of natural gas stream to hydrogen

Analyse demand by Local Distribution Zone (LDZ), to ensure storage capacity estimates are geographically relevant and economically feasible

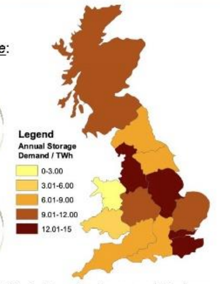

***Fig.1**. Map showing annual H_2 storage demand by LDZ (100% H_2 grid).*

Hydrogen storage capacity estimates:

Determine UKCS fields suitable for inclusion

Calculate H_2 storage capacities:

$$E_H = HHV_H \times \rho_{H,s} \times OGIP \times \frac{\rho_{CH_4,stp}}{\rho_{CH_4,s}} \times UG$$

E_H: energy stored as H_2 working gas; HHV_H: higher heating value of H_2; $\rho_{H,s}$: H_2 density, reservoir conditions; $OGIP$, original gas in place; $\rho_{CH4,stp}$: natural gas density, standard conditions; $\rho_{CH4,s}$: natural gas density, reservoir conditions; UG, fraction of storage volume as working gas.

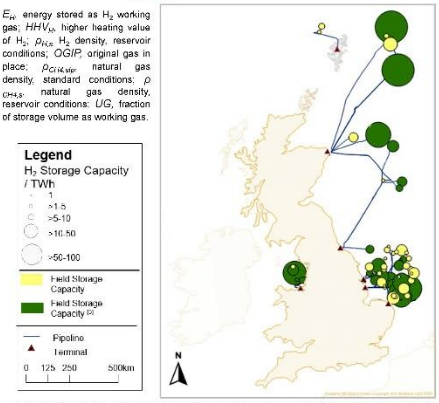

***Fig.2**. Map of H_2 storage capacities and locations of existing pipelines and terminals*

Coupling hydrogen storage with offshore wind:

Determine offshore wind sites suitable for inclusion

Expert elicitation to determine criteria for optimal sector coupling with offshore wind, in the context of green H_2 production

Paired comparison analysis (PCA) to determine relative importance of developed criteria (Table 1)

Rank fields in respect to optimal coupling with offshore wind (OW)

***Table.1**. Criteria weightings, as determined by PCA results*

Criteria	Weighting
H_2 storage capacity	0.21
Operational status	0.19
Length of existing pipeline	0.15
Field type	0.14
Proximity to terminal	0.09
Drive mechanism	0.07
Number of wells	0.05
Water depth	0.04
Proximity to OW	0.03
Age of operation	0.03

***Fig.3**. Map of optimal fields for coupling, according to developed criteria and weightings*

3. Discussion & Conclusions

- A total storage capacity of 3454 TWh determined across 96 fields significantly exceeds the 120 TWh required to meet seasonal domestic heating demands (8.92 TWh for 20% H_2-blending scenario).
- Results of our weighted analysis suggest the best prospects for coupling green H_2 generation and storage in depleted reservoirs are found in the Southern North Sea and East Irish Sea.
- We present a nuanced picture that highlights the benefits of combining high-deliverability blended salt cavern storage and high-capacity offshore storage in depleted hydrocarbon reservoirs, to meet anticipated UK gas demands.
- Further research is needed to assess the technological feasibility of repurposing existing infrastructure for H_2, the deliverability of H_2 storage in potential fields and challenges regarding storage loss due to geochemical/microbial activity in porous reservoirs.

References
[1] IRENA (2020). *Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5°C Climate Goal*. Abu Dhabi, International Renewable Energy Agency.
[2] Amid, A., et al. (2016). "Seasonal storage of hydrogen in a depleted natural gas reservoir." International Journal of Hydrogen Energy **41**(12): 5549-5558.
[3] Mouli-Castillo, J., et al. (2021). "Mapping geological hydrogen storage capacity and regional heating demands: An applied UK case study." Applied Energy **283**: 116348.

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Geochemical reactions in the storage reservoir

[06] Risk of H_2S generation form the H_2 driven reduction of pyrite to pyrrhotite (E. Craenmehr & R. Groenenberg)

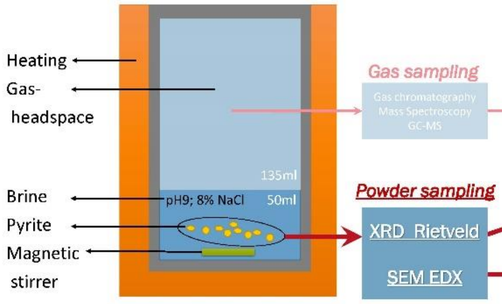
Risk of H_2S generation from the H_2 driven reduction of pyrite to pyrrhotite

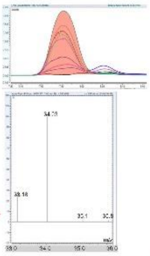
Mixed batch experiments

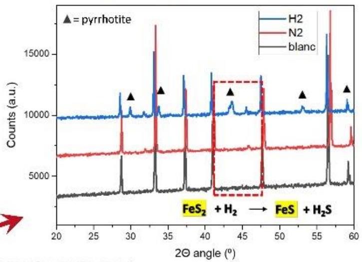
- Developing reactor setup and analyses
- Execution experimental matrix

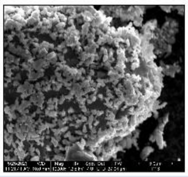
Pyrite → Pyrrhotite

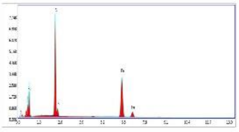
$$FeS_2 + H_2 \rightleftharpoons FeS + H_2S$$





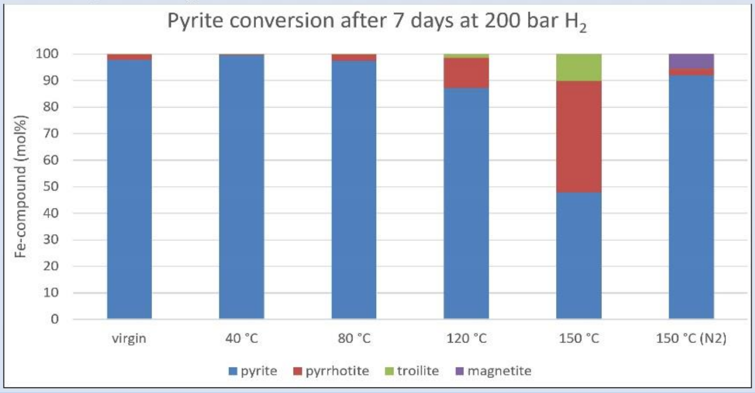


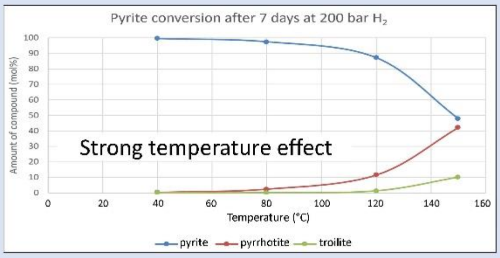


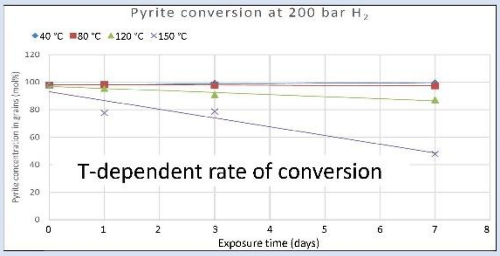


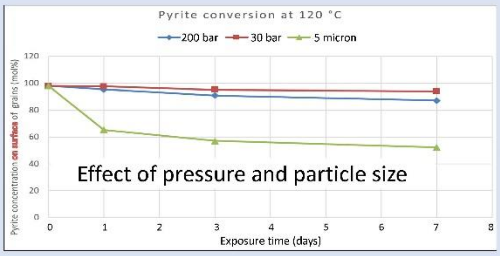
Results

- Rapid FeS_2 reduction >120 °C, and slow at 80 °C









Conclusions and interpretations

- Strong effect of temperature on reaction (and rate)
- Weak(er) but noticeable effect of pressure (P) on reaction rate, possibly due to higher solubility of hydrogen in brine and/or deeper penetration into the particles at higher P
- Reaction strongly dependent on surface area of pyrite available for conversion
- H_2S production rates (calculated): 4-8 mg/day/g pyrite at 120 °C and 200 bar with <40 micron particles (and pH ~9)

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This poster contributes to HyUSPRe WP2, Task 2.3

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Clean Hydrogen Partnership

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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.

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Microbiological activity in the storage reservoir

[07] Unveiling microbial dynamics in subsurface H2 storage environment (part 1): a kinetic study (A.C. Ahn et al.)

Unveiling microbial dynamics in subsurface H_2 storage environment (part 1): A kinetic study

Introduction

Underground H_2 storage in depleted porous reservoirs offers a promising solution for renewable energy storage. However, it also faces challenges stemming from activity of microorganisms in the subsurface such as methanogens, sulfate reducers, and acetogens. These microbes can impact the safe H_2 storage in various ways, including H_2 consumption and the production of contaminants.

$4\,H_2 + CO_2 \rightarrow CH_4 + 2\,H_2O$ **(Methanogenesis)**, $4\,H_2 + SO_4^{-} + H^+ \rightarrow HS^- + 4\,H_2O$ **(Sulfate reduction)**, $4\,H_2 + 2\,CO_2 \rightarrow CH_3\,COOH + 2\,H_2O$ **(Homoacetogenesis)**

Wet lab experiments with reservoir brine samples under relevant storage conditions provide data on hydrogenotrophic microbial kinetics. Subsequently, extrapolation to field simulations through **modelling** allows the prediction of microbial impact on the subsurface H_2 storage.

Results

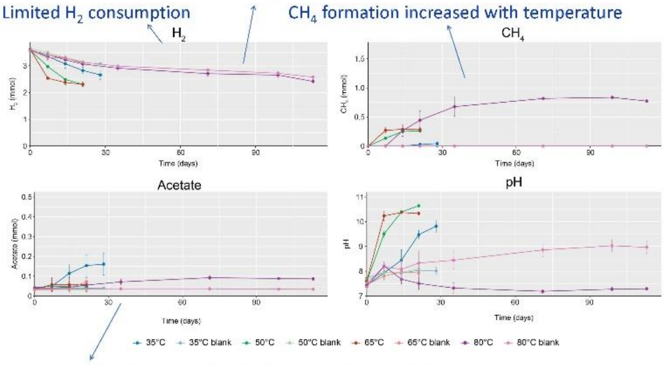
(1) Determination of microbial activity

Incubation under "H_2-only" condition

No H_2 consumption at 80°C

Limited H_2 consumption

CH$_4$ formation increased with temperature



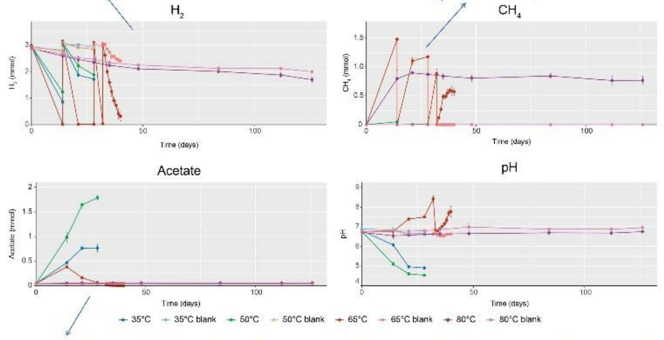
Acetate production peaked at 35°C and declined at higher temperatures

Figure 1. Brine sample incubations at 35, 50, 65 & 80°C with 100% H_2 and $NaHCO_3$. Growth limited by minerals present in the brine and the supplied H_2.

Incubation under "H_2/CO_2-nutrient supplemented" condition

Higher H_2 consumption

CH_4 formation peaks at 65°C



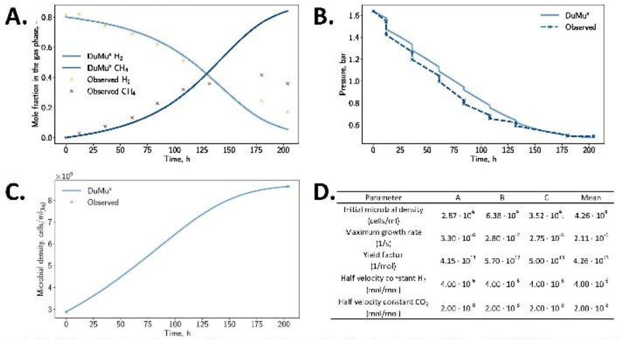
Acetate peaked at 50°C and was also produced by a non-hydrogenotrophic metabolism

Figure 2. Brine sample incubations at 35, 50, 65 & 80°C with 80% H_2/20% CO_2, $NaHCO_3$, and added minerals and vitamins simulating a high-impact scenario. Gas phase of cultures were exchanged multiple times (fluctuation in H_2 and CH_4).

(2) Modelling of kinetic growth parameters

Using Monod equation-based modelling, growth parameters were derived by replicating experiments that targeted methanogens. Laboratory-measured constants, including gas phase pressure and CH_4 and H_2 amounts, were incorporated into the model, enabling precise determination of changes in microbial density.

While the model accurately matches lab observations, microbial growth may be less optimal *in situ*, resulting in lower reaction rates. The model assumes substrate-limited growth, likely in the contact zone between stored and cushion gas. Near the injection well, space limitations may dominate due to continuous substrate supply. Preliminary growth parameters can aid in field-scale risk assessment.



Parameter	A	B	C	Mean
Initial microbial density (cells/ml)	$2.87 \cdot 10^{9}$	$6.38 \cdot 10^{9}$	$3.52 \cdot 10^{9}$	$4.26 \cdot 10^{9}$
Maximum growth rate (1/s)	$3.30 \cdot 10^{-6}$	$2.80 \cdot 10^{-7}$	$2.75 \cdot 10^{-6}$	$2.11 \cdot 10^{-6}$
Yield factor (1/mol)	$4.15 \cdot 10^{13}$	$5.70 \cdot 10^{12}$	$5.00 \cdot 10^{13}$	$4.26 \cdot 10^{13}$
Half velocity constant H_2 (mol/mol)	$4.00 \cdot 10^{-6}$	$4.00 \cdot 10^{-6}$	$4.00 \cdot 10^{-6}$	$4.00 \cdot 10^{-6}$
Half velocity constant CO_2 (mol/mol)	$2.00 \cdot 10^{-8}$	$2.00 \cdot 10^{-8}$	$2.00 \cdot 10^{-8}$	$2.00 \cdot 10^{-8}$

Figure 3. "H_2/CO_2-nutrient supplemented" best modelling match after the last H_2 refilling at 65°C. (A) Gas composition in the headspace; (B) Pressure drop in incubations; (C) Microbial density; (D) Matched growth parameters.

Conclusions

- Modeling microbial growth parameters aids risk assessment using lab data
- Enables evaluation of microbial impact on H_2 storage reservoirs under various conditions
- Despite current limitations, it enhances understanding of microbial kinetics in subsurface environments
- Supports the EU's sustainable energy goals by improving risk assessment and H_2 storage strategies

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This poster contributes to HyUSPRe WP3 Task 3.3

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Hydrogen Underground Storage in Porous Reservoirs HyUSPRe

Clean Hydrogen Partnership

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WAGENINGEN UNIVERSITY & RESEARCH

TU Clausthal

Microbiological activity in the storage reservoir

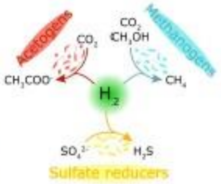
[08] Unveiling microbial dynamics in subsurface H2 storage environment (part 2): a competition study (A.C. Ahn et al.)

Unveiling microbial dynamics in subsurface H_2 storage environment (part 2): A competition study

Introduction

Interest in subsurface H_2 storage is increasing, yet our understanding of the microbial community inhabiting these environments and how they will be influenced by H_2 storage remains limited. Therefore, understanding the effect of environmental conditions on microorganisms is of tremendous importance to forecast H_2 losses, perform risk assessment and ensure effective reservoir monitoring.

Microbial community dynamics and **competitions** were analyzed from **wet lab experiments** with reservoir brine samples using amplicon sequence analysis based on 16S rRNA gene V4 region.



Results

(3) Microbial community composition analysis

The analysis of the relative microbial community composition identifies potential contributors to the observed metabolic activities in the incubations:.

Incubation under "H_2-only" condition

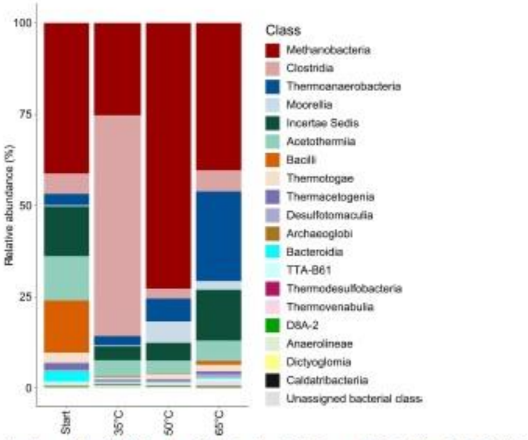


Figure 1. Relative abundance of the microbial community at class level of brine sample incubations at 35, 50, 65°C with 100% H_2 and $NaHCO_3$. Samples were taken at the start and at the end of each incubation cycle.

Incubation under "H_2/CO_2-nutrient supplemented" condition

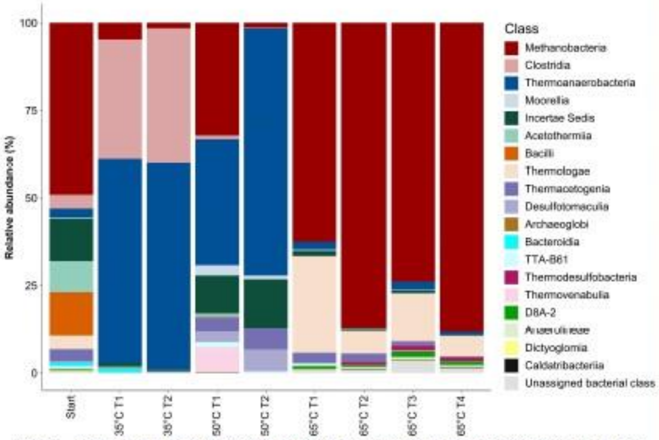


Figure 2. . Relative abundance of the microbial community at class level of brine sample incubations at 35, 50, 65°C with 80% H_2/20% CO_2, $NaHCO_3$, and added minerals and vitamins. Samples were taken at the start and at the end of each incubation cycle.

The main takeaways from this analysis are:

- Acetate production occurred via homoacetogenesis and fermentative pathways in both conditions
- Acetogenesis may have been performed by strains of Clostridia, Thermoanaerobacteria, and Moorelia under both conditions
- Acetate is likely also produced by species of the Acetothermiia phylum in "H_2-only" conditions
- Strains of Thermotogae and Thermacetogenia class likely contributed to acetate production in "H_2/CO_2-nutrient supplemented" condition
- Thermacetogenia class could syntrophically reduce acetate with Methanobacteria, possibly explaining acetate reduction at 65°C
- Under both conditions, hydrogenotrophic CH_4 production was likely produced by strains of the Methanobacteria class
- Nutrient supplemented incubations promoted microbial competition resulting in an overall decrease of microbial diversity evenness

Conclusions

- Findings highlight the complex interplay between environmental factors, nutrient availability, and microbial community structure
- Understanding these connections is crucial for predicting subsurface ecosystem changes and H_2 storage applications
- Further research needed on the metabolic capabilities of dominant microbial groups and their environmental interactions
- Essential for comprehending the dynamics of subsurface microbial ecosystems

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This poster contributes to HyUSPRe WP3 Task 3.5

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Hydrogen reservoir flow behavior

[09] Experimental Investigations of Molecular Diffusion and Mechanical Dispersion during UHS (J. Michelsen et al.)

Experimental Investigations of Molecular Diffusion and Mechanical Dispersion during UHS

Introduction

In Underground hydrogen storage (UHS), the mixing behaviour of injected hydrogen and residual natural gas (primarily methane) in the porous reservoir is crucial. This mixing is governed by molecular diffusion and mechanical dispersion. Laboratory experiments measured these processes. Molecular diffusion, driven by concentration gradients, occurs even without pressure differences, while mechanical dispersion results from pressure-driven fluid movement through the pore space. Understanding and quantifying these processes are essential for predicting the performance of underground hydrogen storage in porous reservoirs with the help of numerical modelling.

Molecular diffusion

- Driven by concentration gradients, even without pressure differences.
- Molecular diffusion can take place under both stationary and unsteady conditions.
- Fick's laws and can be used to estimate diffusive flux. Fick's first law states that the diffusion flux is directly proportional to the concentration gradient.
- In a porous medium the diffusivity is usually reduced compared to the free gaseous diffusivity because the gas has less space and must travel a longer distance through it (tortuosity).
- For binary systems the diffusive flux of gas components in a porous medium can be described by the following relation:

$$J_{\mathrm{diff}}^{k} = -\rho D_{\mathrm{eff}} \nabla c^{k}$$

where J_{diff}^{k} is the diffusive flux of component k in mol/m²/s, ρ is the molar density of gas in mol/m³, D_{eff} is the binary effective diffusion coefficient in m²/s and ∇c^{k} is the gradient of the mole fraction of component k.

Experimental procedure

- The main component is a Hassler cell, which comprises two chambers and a rock sample (6 cm length, 3 cm diameter) in the middle.
- Initially, the cell and the pores of the core sample are filled with hydrogen. During the measurement, methane is injected at a constant rate. The composition of the outflowing gas is analyzed by a gas chromatograph every 5 minutes.
- Based on the measurement results, effective diffusion coefficients are calculated by comparing the measurements to one-dimensional simulation in COMSOL Multiphysics.

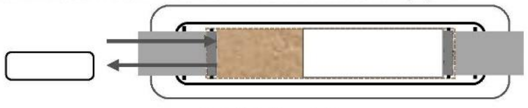

Fig. 1: Sketch of the core holder

- Seven storage rock samples were used and one Bentheimer sandstone sample (29 measurements in total):
  - Every sample was measured at the specific site conditions and at reference conditions (100 bar, 40 °C).
  - The Bentheimer sandstone was used to investigate the influence of pressure, temperature and water saturation on diffusion.

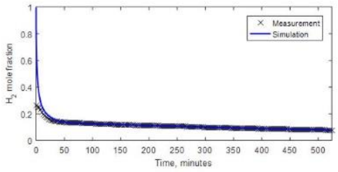

Fig. 2: Comparison of the simulation results with a diffusion measurement in COMSOL Multiphysics

Results

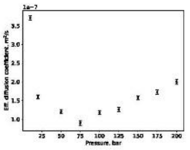

Fig. 3: Effective diffusion coefficient vs. pressure for the Bentheimer sandstone sample at 40 °C

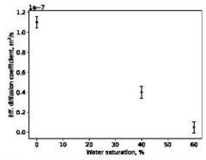

Fig. 4: Effective diffusion coefficient vs. water saturation for the Bentheimer sandstone sample at 100 bar and 40 °C

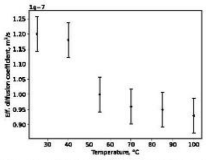

Fig. 5: Effective diffusion coefficient vs. temperature for the Bentheimer sandstone sample at 100 bar

- The experimental data was used to develop and calibrate a correlation, which can be used in numerical simulation to predict mixing effects during UHS (Hogeweg et al. [2024]):

$$D_{pm}^{AB} = \phi\, \tau(\phi, S_g, k) S_g\, D_{bulk}^{AB}(p, T) \text{ with } \tau = \phi \cdot S_g \cdot k_{\mathrm{eff}}^{\frac{1}{5}} \cdot 176.916\, m^{-\frac{2}{5}}$$

where D_{pm}^{AB} is effective binary diffusion coefficient of the porous media in m^2/s, ϕ is the porosity, τ is the tortuosity factor of the porous medium, S_g is the gas saturation, D_{bulk}^{AB} is the binary diffusion coefficient for the bulk medium in m^2/s and k_{eff} is the effective permeability in m^2.

Mechanical dispersion

- Caused by the movement of fluids in porous media/flow velocity fluctuations across different scales: Pore-size distribution, tortuosity, heterogeneity
- At microscopic scale, larger pores typically exhibit higher velocities
- Mechanical dispersion can be mathematically described by assuming a linear relationship with the flow velocity (Scheidegger [1961]):

$$J_{\mathrm{disp}}^{k} = -\rho \alpha U \nabla x^{k}$$

where J_{disp}^{k} is the dispersive flux of component k in mol/m²/s, ρ is the molar density of gas in mol/m³, α is the mechanical dispersivity in m, U is the true flow velocity in m/s and ∇x^{k} is the gradient of the mole fraction of component k.

Experimental procedure

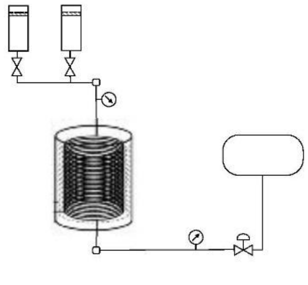

Fig. 6: Simplified sketch of the experimental setup

- The experimental apparatus comprised a 25 m long slim tube coil filled with glass beads to simulate a porous medium (35 % porosity).
- The slim tube coil was filled with methane; during the measurements, hydrogen was continuously introduced, displacing the methane.
- The outflowing gas mixture was analyzed for its composition using a gas chromatograph.
- Based on the measurements longitudinal dispersivites were determined by using the following equation (Bear, 2013):

$$\alpha_L = \frac{U^2}{4\pi i^2}$$

where α_L is the longitudinal dispersivity in m, U is the true flow velocity in m/s and i is the slope of the curve of H_2 mole fraction of 0.5 in 1/s (see Fig. 7)

- 13 measurements were performed at temperatures from 20 to 100 °C, pressures from 50 to 150 bar and flow velocities from 5 to 50 m/day.

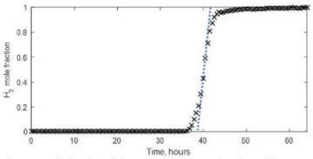

Fig. 7: H_2 mole fraction of the outflowing gas vs. time (15 m/day, 100 bar, 40 °C)

Results

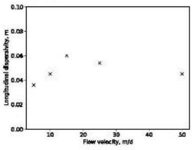

Fig. 8: Dispersivity vs. flow velocity (pressure 100 bar, temperature 40 °C):

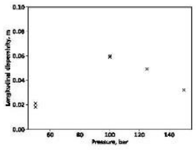

Fig. 9: Dispersivity vs. pressure at 40 °C (flow velocity 15 m/day, temperature 40 °C)

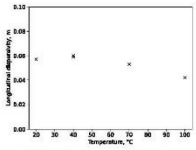

Fig. 10: Dispersivity vs. temperature (pressure 100 bar, temperature 40 °C):

Conclusions and outlook

- The values for the effective diffusion coefficient range from $5.0 \cdot 10^{-9}$ to $2.3 \cdot 10^{-7}$ m²/s. The plotting of the effective diffusion coefficients show clear trends, which, however, are partly different than calculated by conventional correlations.
- The determined longitudinal dispersivities lie between 0.018 and 0.060 m. Dispersivity varies with pressure, temperature, and flow velocity. Scheidegger's theory predicts gas mixing under subsurface conditions, but is not capturing all effects.
- The developed correlations can be used in numerical simulators to predict mixing effects during hydrogen storage in the subsurface.

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Durability and integrity of well and rock materials

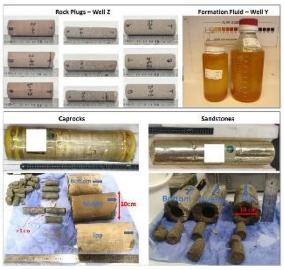
[10] Impact of cyclic hydrogen storage on porous reservoirs' flow and mechanical properties (V. Soustelle et al.)

Experimental data on the effect of H2 cyclic injection/depletion on flow and mechanical properties of porous reservoir rocks and caprocks

Motivations:

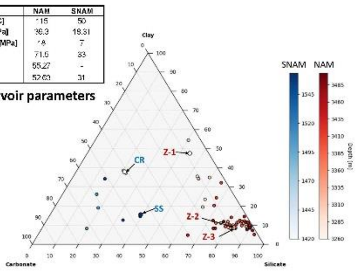
- Assess the impact of hydrogen-rock reactions and cyclic pressure loading on the mechanical and flow properties of porous reservoir rocks and caprocks.
- Provide a preliminary overview of the geomechanical integrity of potential reservoir candidates for Underground Hydrogen Storage (UHS).

Samples Description:



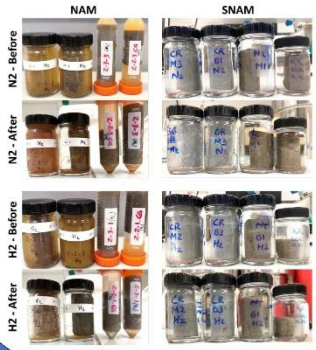
	NAM	SNAM
Temp. [°C]	115	50
$P_{initial}$ [MPa]	39.3	18.31
$P_{depleted}$ [MPa]	18	7
S_v [MPa]	71.5	33
S_H [MPa]	55.27	-
S_h [MPa]	52.63	31

Reservoir parameters

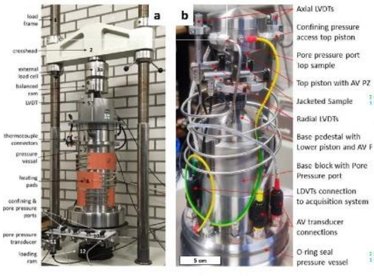


Experimental Methods:

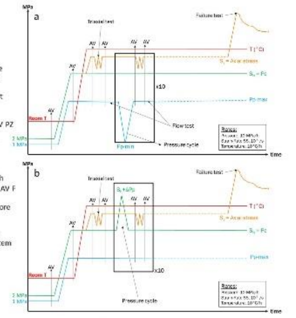
Exposure test: H2 & N2 - 20 MPa - 100 °C - 60 Days



Triaxial tests

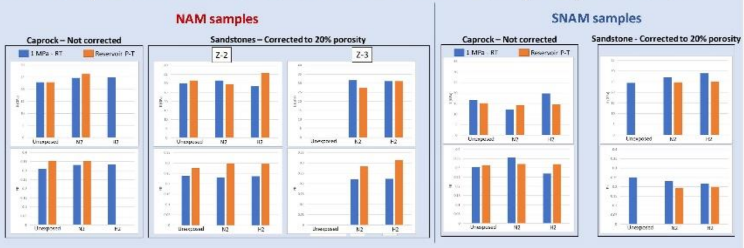


Experimental Setup (TNO Utrecht)

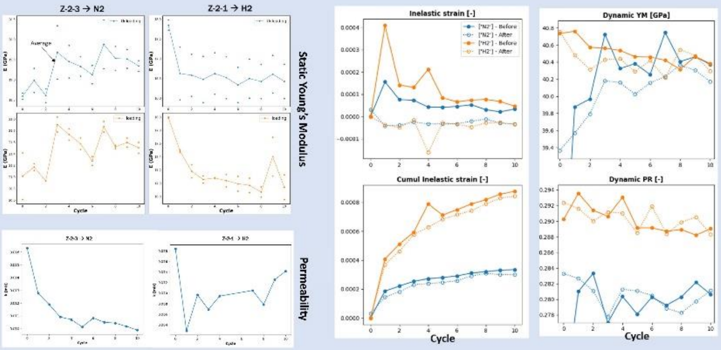


Experimental Protocol for sandstones (top) and caprocks (bottom)

H2 exposure effect on Mechanical properties:



H2 exposure + Cyclic loading effect on Flow and Mechanical properties:



Conclusions:

- **Brine Composition:** No consistent significant difference after H2 or N2 exposure, except for pH, K, and Si at TNO labs.
- **Elastic parameters:** H2 exposure led to less than 10% change in Young's Modulus, suggesting limited impact on mechanical integrity. Changes varied based on testing conditions (initial vs. reservoir conditions).
- **Cyclic Loading Tests:**
  - *Mechanical Behavior:* H2-exposed samples showed increased inelastic axial strain with each cycle. Overall impact on mechanical integrity after ten cycles was under 1%.
  - *Permeability:* Sharp decrease in permeability after first cycle for both H2- and N2-exposed samples. Unexpected increase in permeability in subsequent cycles for H2-exposed samples, indicating complex response.

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Durability and integrity of well and rock materials

[11] Microbial influenced corrosion and potential impact of H2 on subsurface storage processing facility elements (J. Dykstra et al.)

Microbial influenced corrosion and potential impact of H_2 on subsurface storage processing facility elements

Introduction

Underground H_2 storage in depleted porous reservoirs offers a promising solution for renewable energy storage. However, it also faces challenges stemming from the potential microbial microorganisms in the subsurface such as methanogens, sulfate reducers, and acetogens. These microbes can impact the safe H_2 storage in various ways, including H_2 consumption and the production of contaminants and cause Microbiologically Influenced Corrosion (MIC). This poster discusses the work conducted to investigate the potential impact of high partial pressure of H_2 on MIC. MIC has been proposed to occur through different mechanisms through either direct electron transfer (DIMET) or H_2-mediated electron transfer (HIMET) and as such could be potentially impacted by the partial pressure of H_2.

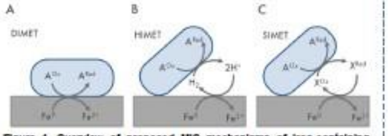

Figure 1. Overview of proposed MIC mechanisms of iron-containing metals in anoxic environments via either (A) H_2-mediated iron-to-microbe electron transfer (HIMET), (B) shuttle-mediated iron-to-microbe electron transfer (SIMET), or (C) direct iron-to-microbe electron transfer (DIMET). A^{Ox}; oxidized electron acceptor. A^{Red}; reduced electron acceptor. X^{Ox}; oxidized soluble electron shuttle. X^{Red}, reduced soluble electron shuttle. The electron acceptor could be sulfate, carbon dioxide, etc.

Results

(1) Initial MIC Experiment

In an initial attempt to elucidate the effect of H_2 on MIC, carbon steel coupons were exposed to a microbial community incubated in medium amended with 25 mM Na_2SO_4 and 5 mM VFAs as carbon source (2.5 mM acetate, 1.25 mM propionate, and 1.25 mM butyrate) and reduced with 1 mM Na_2S under either N_2/CO_2 (80/20 v/v%) or H_2/CO_2 (80/20 v/v%) headspace. Abiotic controls were added to keep track of abiotic corrosion.

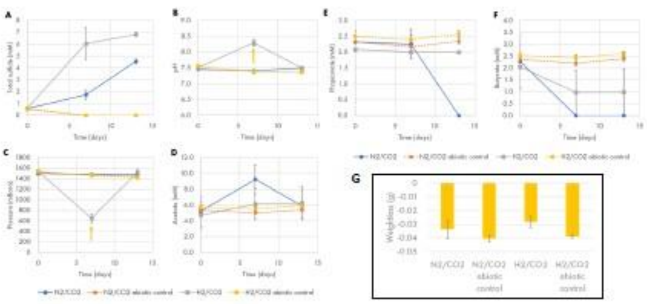

Figure 1. Results for the initial MIC Experiment showing sulfide formation (A), change in pH (B) and pressure (C), acetate (D), propionate (E), and butyrate (F) concentrations. Data is shown as the average ± std of biological duplicates. At day 7, the pH was adjusted back to pH 7.5 and H2 was added to the biotic H_2/CO_2 cultures, indicated by the arrows. (G) The weight loss of the coupons (g) calculated from the average weight of each coupon (see Materials and methods) before and after the experiment from the initial MIC experiment inoculated with an enriched microbial consortium using metal coupons. Data is shown as the average ± std of biological duplicates.

Sulfide was produced in both H_2 and N_2 headspace incubations, indicating the presence of active sulfate-reducing microorganisms (Figure 1A). More sulfide was produced in conditions with H_2/CO_2 compared to N_2/CO_2. In contrast to N_2/CO_2 conditions, in the H_2/CO_2 conditions propionate and butyrate were completely consumed (Figure 1D-F). VFA levels remained constant in the abiotic controls. For the bottles with H_2 the pH increased above pH 8 accompanied by a decrease in pressure thus indicating consumption of H_2 (Figure 1B-C). Since a pH of 8 or higher may limit microbial activity, the pH was manually adjusted to 7.5. Generation of sulfide resulted in a subsequent significant generation of FeS scale onto the corrosion coupons. Measurement of the weight loss of the coupons showed no significant weight loss for any of the incubations (Figure 1G).

(2) 2nd experiment MIC Experiment

Given the high generation of sulfide resulting on large FeS scale on the corrosion coupons, not allowing MIC to develop, a new set of experiments was designed. The bottles with carbon steel coupons were inoculated, and first given time to generate a biofilm before introduction of H_2 into the relevant bottles. Notably, coupons in presence of H_2 were corroded to a much lower extent than coupons in presence of N_2.

Conclusions

This report discussed the work conducted to investigate the potential impact of high partial pressure of H_2 on MIC. In the initial experiment, sulfate reduction under H_2/CO_2 generated extensive amounts of sulfide resulting in a significant FeS layer that cover the coupon after a few days of incubation which may have influenced MIC. Interestingly, in the second experiment, the metal coupons were corroded to a much lower extent when hydrogen was present in excess. These initial findings seem to suggest that H_2 appears to be the preferred electron donor rather than metallic iron, implying that MIC is therefore expected to be less severe in presence of higher partial pressures of H_2.

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This poster contributes to HyUSPRe WP5 Task 5.5

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Hydrogen Underground Storage in Porous Reservoirs
HyUSPRe

Clean Hydrogen Partnership

Co-funded by the European Union

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.

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Integrative multi-scale modelling and guidance for suitability assessment

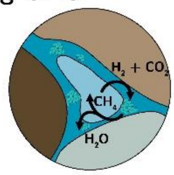
[12] Numerical Simulation of Bio-Geo-Reactive Transport during UHS - A Modelling Approach (S. Hogeweg et al.)

Numerical Simulation of Bio-Geo-Reactive Transport during UHS - A Modelling Approach

Introduction

The increasing share of renewable energy sources with its characteristic fluctuations amplifies the demand for sustainable energy storage. Hydrogen storage in porous rocks in the subsurface offers a suitable potential to balance seasonal changes in production and demand at a large scale. In the reservoir the hydrodynamics will behave differently than natural gas due to hydrogen's unique properties and the presence of hydrogen may induce bio- and geochemical reactions leading to a reduced efficiency of the storage process.

Bio- and geochemical reactions during UHS



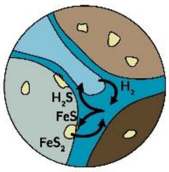
The presence of hydrogen-consuming microorganisms can lead to a progressive hydrogen loss and may yield contamination:

- Methanation:

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$$

- Sulfate-reduction:

$$5H_2 + SO_4^{-2} \rightarrow H_2S + 4H_2O$$



Hydrogen may interact with the minerals, leading to changes within the rock and fluid composition:

- Pyrite-to-pyrrhotite reduction may lead to additional hydrogen sulfide contamination and is therefore accepted as one of the most critical reactions:

$$FeS_2 + H_2 \rightarrow FeS + H_2S$$

Mathematical model

The mathematical model developed by Hagemann [2018] was extended by the geochemical reaction of pyrite-to-pyrrhotite reduction. Besides the mass balance for components in the fluid phase, the solid phase behaves dynamically, and a material balance equation for each solid component has to be solved:

$$\frac{\partial \phi \sum_{\alpha=g,w} \varrho_\alpha c_\alpha^\kappa S_\alpha}{\partial t} = \nabla \cdot \left(\sum_{\alpha=g,w} \varrho_\alpha c_\alpha^\kappa u_\alpha + J_\alpha^\kappa \right) = q^\kappa$$

$$\varrho^{\kappa_s} \frac{\partial \phi_s^{\kappa_s}}{\partial t} = q^{\kappa_s}$$

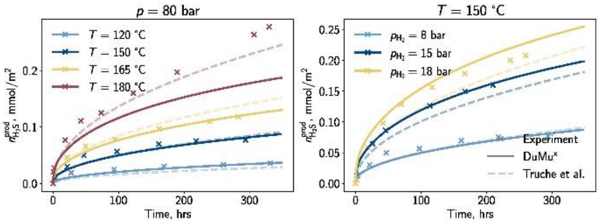
The changes in the fluid and solid phases are represented by the source term:

$$q^\kappa = q_{bio}^\kappa + q_{geo}^\kappa + q_{well}^\kappa$$

The geochemical reaction of pyrite-to-pyrrhotite is assumed to be comparatively slow and, therefore, implemented as a kinetic reaction. Based on laboratory observations from Truche et al. [2010], the kinetic model was calibrated:

$$q_{geo}^\kappa = \gamma_{geo}^\kappa \left(A_s^{r_s} \, k \left(1 - \frac{Q_m}{K_m} \right)^\theta \right) \phi_s^{r_s}$$

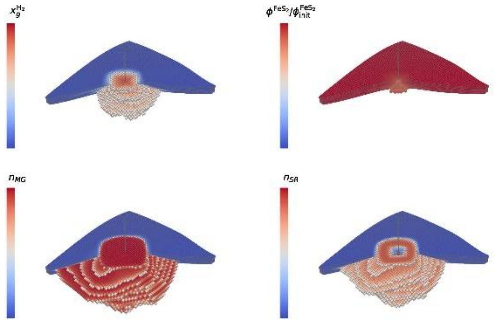
Results of geochemical modelling

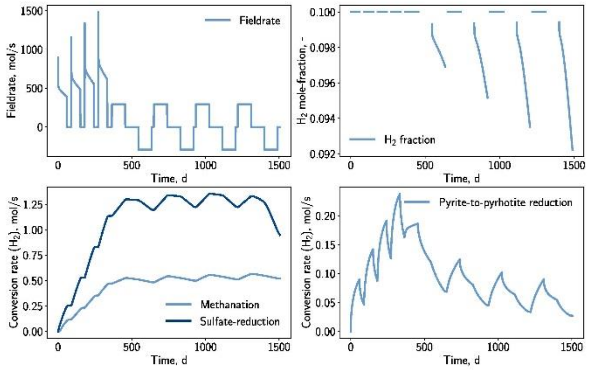


Numerical implementation in DuMu^x

The mathematical model is implemented in the open-source simulator DuMu^x, which is in development by the University of Stuttgart and allows to model the reactive transport in porous media. To test the implementation, a recently developed benchmark scenario (Hogeweg et al. [2022]) is used.

Results of field-scale simulations





Conclusions and outlook

- The developed model allows to simulate reactive transport processes in porous formations with bio- and geochemical reactions
- The consumption of hydrogen leads to the production of methane and contamination with hydrogen sulfide
- The process of molecular diffusion was calibrated by a correlation developed from laboratory observations from WP4
- The reaction process could be calibrated by laboratory observations whereby it is assumed that these reactions could occur slower in reality
- Consequently, demonstration and pilot projects are required to verify the observations from the laboratory and calibrate the field-scale model further

References

1. Hagemann, B. Numerical and Analytical Modeling of Gas Mixing and Bio-Reactive Transport During Underground Hydrogen Storage. vol. Band 50 (Cuvillier Verlag, Göttingen, 2018).
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Integrative multi-scale modelling and guidance for suitability assessment

[13] Guidelines for reservoir and site suitability assessments in hydrogen storage: advancing from TRL 4 to in-field demonstration at TRL 5 (F. Farajimoghadam et al.)

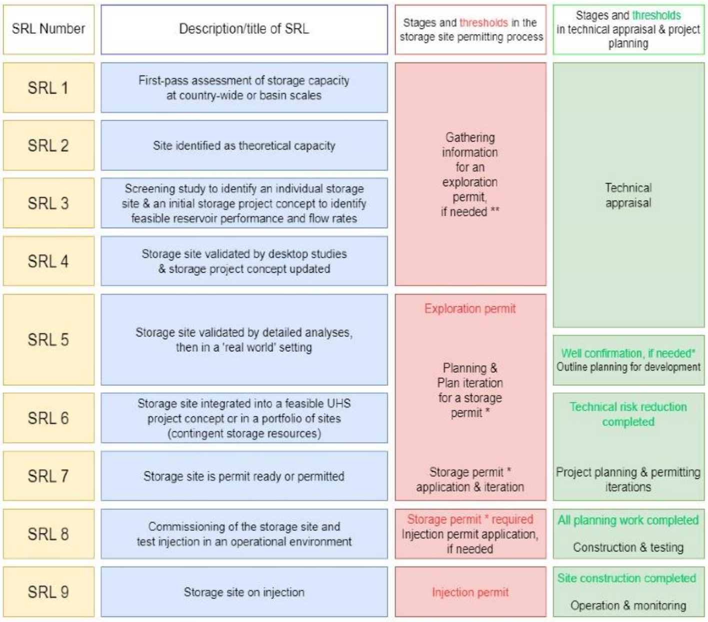
Guidelines for reservoir and site suitability assessments in hydrogen storage

Hydrogen Storage Site Evaluation Process:

Objective: Assess technical feasibility of underground hydrogen storage in porous formations.

Pre-feasibility (SRL 1-4):

- Use available data for preliminary evaluation.
- Assess geological suitability and caprock integrity.
- Perform initial reservoir simulations.
- Define exclusion criteria (e.g., shallow formations, high seismic activity).



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 *	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
SRL 7	Storage site is permit ready or permitted	Storage permit * application & iteration	Project planning & permitting iterations
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

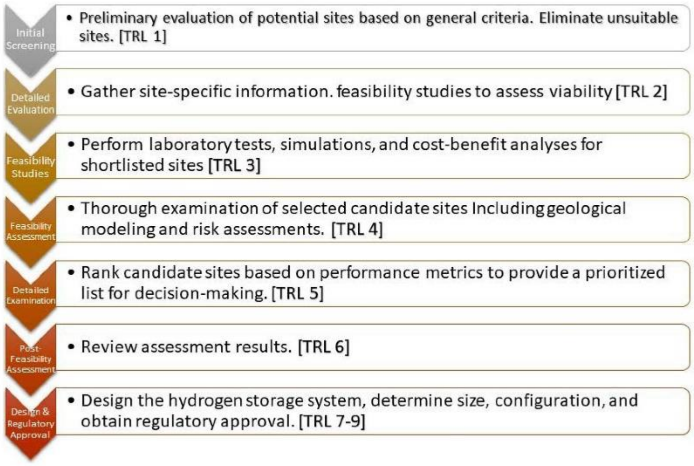
* Equivalent of storage permit relevant to national jurisdiction

Feasibility (SRL 5):

- Drill exploratory wells for physical property data.
- Analyze core samples for mineral composition and stability.
- Conduct modeling simulations and reservoir evaluations.
- Estimate costs: drilling, well completion, infrastructure, operations.

Post-feasibility (SRL 6-9):

- Conduct Environmental Impact Assessment (EIA).
- Engage with local communities and stakeholders.
- Evaluate technical, economic, and environmental feasibility.



- 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]

Decision-making:

- Review results and perform due diligence.
- Design storage system, obtain regulatory approval.
- Construct and monitor facilities for safety and efficiency.

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Integrative multi-scale modelling and guidance for suitability assessment

[14] Numerical modeling of bio-reactive transport during underground hydrogen storage – A benchmark study (N. Khoshnevis Gargar et al.)

NUMERICAL MODELING OF BIO-REACTIVE TRANSPORT DURING UNDERGROUND HYDROGEN STORAGE – A BENCHMARK STUDY

Theory - Microbial activity

Monod-model in DuMux

Methanogenesis: $4H_2 + CO_2 \longrightarrow CH_4 + H_2O$

$$R_{m,n} = \psi_{max}^{growth}\left(\frac{c_w^{H2}}{\alpha_{H2} + c_w^{H2}}\right)\left(\frac{c_w^{CO2}}{\alpha_{CO2} + c_w^{CO2}}\right) n s_w - \frac{b}{n^*} n^2 s_w$$

$$R_{m,k} = \phi \gamma^k \frac{\psi_{max}^{growth}}{Y_{H2}\gamma^{H2}}\left(\frac{c_w^{H2}}{\alpha_{H2} + c_w^{H2}}\right)\left(\frac{c_w^{CO2}}{\alpha_{CO2} + c_w^{CO2}}\right) n s_w$$

Arrhenius-model in GEM-CMG

Growth: $4H_2 + CO_2 + n \longrightarrow CH_4 + H_2O + (1+\varepsilon)n$

Decay: $n \longrightarrow H_2O$

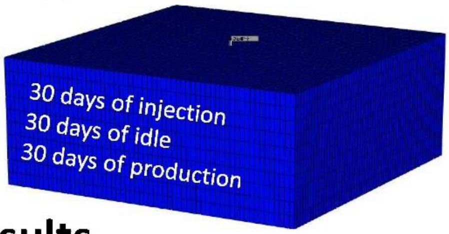
$$R_{Ar,n} = \varepsilon F_1 (m_w^{H2})^{\alpha} (m_w^{CO2})^{\beta} (m_w^{n}) - F_2 (m_w^{n})^2$$

$$R_{Ar,k} = \gamma^k F_1 (m_w^{H2})^{\alpha} (m_w^{CO2})^{\beta} (m_w^{n})$$

n	bacteria population	c_w	mole fraction in water phase	m_w	Molality in water phase
α	half-velocity constant	γ	stochiometric coefficient	F_1, F_2	Pre-exponential factor
Y	yield coefficient (number of generated microbial cell for each consumed mole of H_2)	$R_{m,n}$, $R_{m,k}$	Monod reaction rate for bacteria and component	$R_{Ar,n}$, $R_{Ar,k}$	Arrhenius reaction rate for bacteria and component

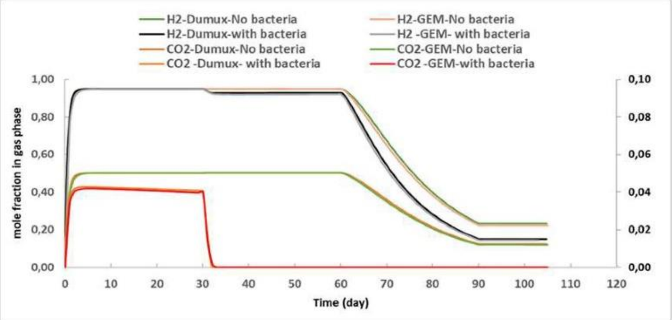
$$R_{m,n} = R_{Ar,n} \quad , \quad R_{m,k} = R_{Ar,k} \Longrightarrow F_1 = \frac{\psi_{max}^{growth} k_n}{Y_{H2}\gamma^{H2}}, \varepsilon = \frac{Y_{H2}\gamma^{H2}}{k_n}, F_1 = \frac{b k_n}{n^*}, k_n = \frac{MW_n}{mass\ of\ bacteria}$$

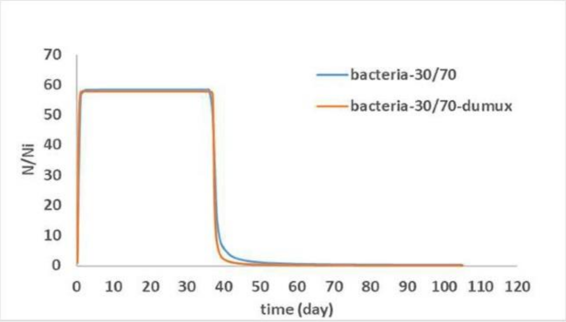
Model


30 days of injection
30 days of idle
30 days of production

Number of grid cells	61x61x10
Grid sizes (m)	25x25x5
Porosity (-)	0.2
Horizontal permeability (mD)	100
Vertical permeability (mD)	10
Top (datum) depth (m)	3368
Reservoir initial pressure (bar)	100
Reservoir initial temperature (°C)	40
Initial gas composition	100% CH_4
Injection rate (m^3/day)	$1x10^6$
Injection gas composition	95% H_2, 5% CO_2
Initial water saturation	0.2
initial bacteria density, n* (1/m3)	$6.88x10^{11}$

Results





Cum H2 produced/cumH2 injected	95% H2-5% CO2	99% H2-1% CO2	70% H2-30% CO2	95% H2-5% CO2 (slow growth)
Without Bacteria	68.63%	68.28%	70.27%	68.63%
With Bacteria	58.8%	66.65%	0%	65.54%

Khoshnevis, N., S. Hogeweg, C. Goncalves Machado, and B. Hagemann. "Numerical Modeling of Bio-Reactive Transport During Underground Hydrogen Storage–a Benchmark Study." In The Fourth EAGE Global Energy Transition Conference and Exhibition, vol. 2023, no. 1, pp. 1-5. European Association of Geoscientists & Engineers, 2023

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Hydrogen Underground Storage in Porous Reservoirs
HyUSPRe
Clean Hydrogen Partnership
Co-funded by the European Union

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TNO innovation for life
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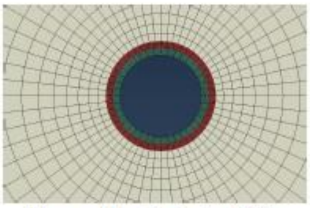
Integrative multi-scale modelling and guidance for suitability assessment

[15] Well integrity and leakage analysis for a hydrogen storage well (A. Moghadam et al.)

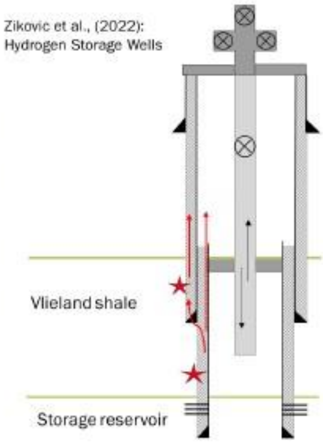
Well Integrity and Leakage Analysis for a Hydrogen Storage Well

Introduction

In this work we developed a case study for the re-use of a well in a gas field in the North Sea for hydrogen storage, in terms of leakage and cement integrity.



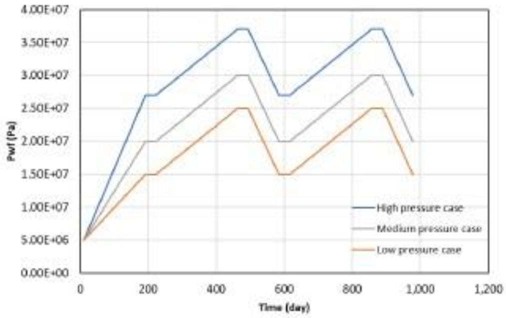
Near well region in the finite element model



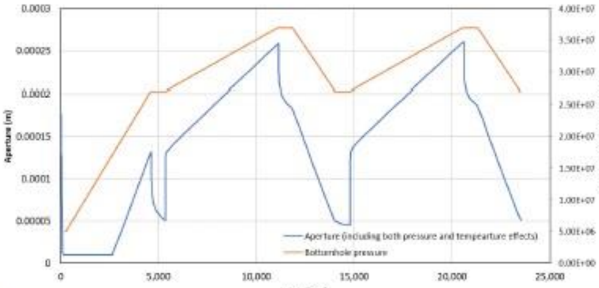
Operational conditions

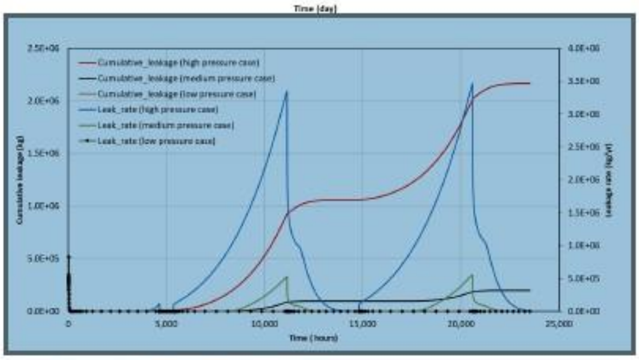
Three working pressure ranges were considered:

- High pressure case: 27 MPa min. P - 37 MPa max. P
- Med pressure case: 20 MPa min. P - 30 MPa max. P
- Low pressure case: 15 MPa min. P - 25 MPa max. P



Results





Conclusions

- Microannuli size changes during cycles of injection and production
- Results indicate that the injection pressure controls the rate of leakage out of the storage complex (ballooning effect)
- Limiting the maximum pressure (max. P) can reduce the leakage rate at the cost of storage capacity
- Non-Darcy flow coefficient for hydrogen should be evaluated in the future
- Proposed workflow provides a quantitative framework to optimize the storage strategy

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This poster contributes to HyUSPRe WP6, Task 6.1

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Hydrogen Underground Storage in Porous Reservoirs HyUSPRe

Clean Hydrogen Partnership

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Techno-economic assessment of EU scenarios for hydrogen storage

[16] Underground storage in EU scale hydrogen system scenarios (T. Groß & P. Dunkel)

Underground Storage in EU-scale Hydrogen System Scenarios

1. Introduction

To assess the potential role of hydrogen storages in porous reservoirs within a future European hydrogen system, a **European energy system model** has been developed that covers the transition from **2030 to 2050**, incorporating the greenhouse gas emission reduction targets.

Model:

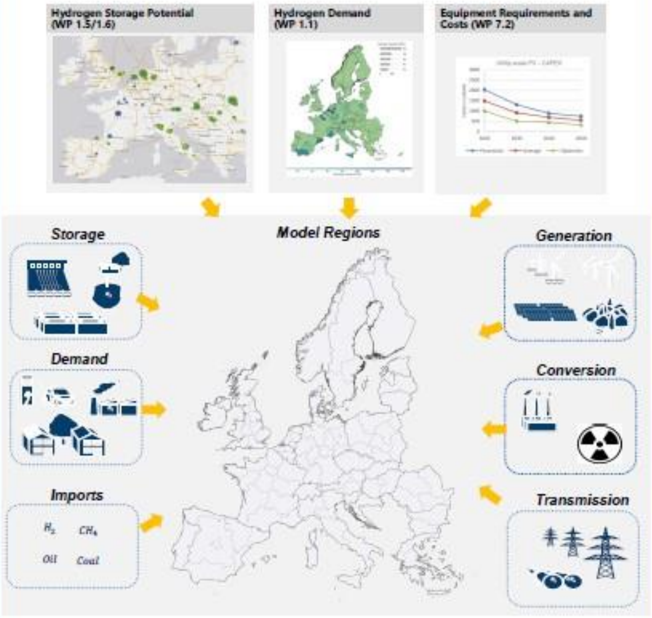
- **Minimizes the total annual costs** of the system designs including infrastructure (**ideal system from a techno-economic perspective)**
- **Techno-economic assessment** of the European energy system with high spatial and temporal resolution

Goal:

- Determine role of porous storage systems as potential hydrogen storage facilities in Europe's future energy system.

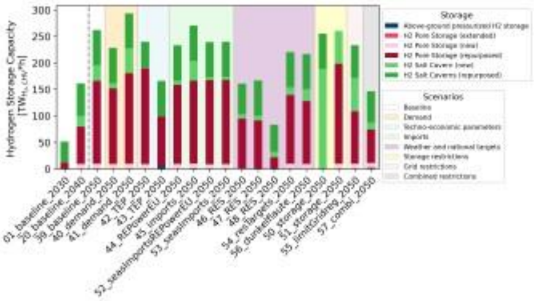
2. Methodology

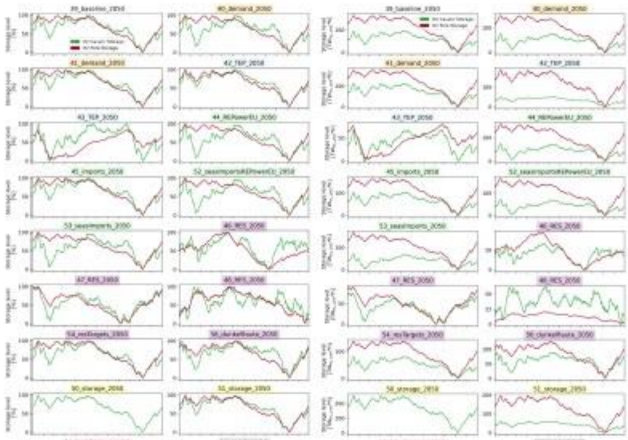
Geographical scope: EU-27 + UK, Switzerland, and Norway
Spatial resolution: 100 onshore regions (NUTS-1) + 76 offshore regions
Temporal resolution: hourly



3. Results

- <u>Necessity of UHS</u>: UHS is **required for a successful and affordable transformation** of the European energy system.
- <u>Future Capacity</u>: Share of **pore storage** as hydrogen storage increases to more than **60% of the required hydrogen storage capacity** by 2050.
- <u>Determinants</u>:
  - ***Techno-economic assumptions*** strongly impact system design
  - ***Electricity mix*** of the energy system affects hydrogen production patterns and favorable locations
  - Linear correlation between ***hydrogen demand*** and storage capacity
  - Unavailability of pore storage leads to more centralized storage
  - Quantity, geographical distribution, and temporal availability of ***hydrogen imports*** affects required storage capacity
  - ***Meteorological conditions*** dictate surplus residual electricity and therefore required UHS capacity
  - Potential ***grid limitations*** prevent significant hydrogen imports from North-Africa and the UK





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Techno-economic assessment of EU scenarios for hydrogen storage

[17] Stakeholder analysis of underground hydrogen storage (D. Markova et al.)

Stakeholder Analysis of Underground Hydrogen Storage

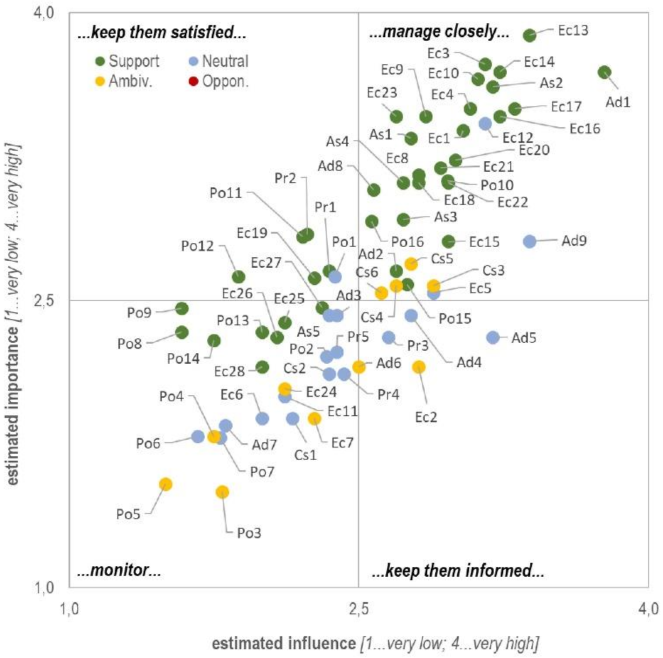
Goal

The analysis assessed stakeholder perspectives on underground hydrogen storage in Europe by **influence**, **importance** and **general attitude**. Stakeholder identification was based on consortium expertise, literature and feedback loops. In total, **69 stakeholders** in **6 categories** were identified.

Results

Overall, **26 experts** contributed to the assessment through a **questionnaire**, supplemented by **interviews** within the project consortium. The main findings are as follows:

Influence, importance and attitude of stakeholders



Overview of assessed stakeholders per category

Economic Players (28)

Ec1	Renewable energy produces
Ec2	Fossil energy produces
Ec3	Hydrogen produces
Ec4	Hydrogen derivatives prod.
Ec5	Natural gas produces
Ec6	Biogas produces
Ec7	LNG produces
Ec8	Energy trading produces
Ec9	Renewable energy trading c.
Ec10	Importers of hydrogen
Ec11	Small-scale storage operators
Ec12	Large-scale storage operators
Ec13	Porous storage operators
Ec14	Cavern storage operators
Ec15	Electrical grid operators
Ec16	Gas network operators
Ec17	Pipeline network operators
Ec18	Transportation terminal oper.
Ec19	Road-transport infrastr. oper.
Ec20	Iron & Steel industry
Ec21	Chemical industry
Ec22	Refineries
Ec23	Supplier hydr. & renew. techn.
Ec24	Suppliers of fossil techn.
Ec25	Road transport companies
Ec26	Rail transport companies
Ec27	Maritime transport companies
Ec28	Aviation transport companies

Administrations (9)

Ad1	European Commission
Ad2	Economic Chambers
Ad3	National trade associations
Ad4	Central environmental auth.
Ad5	National approval authorities
Ad6	Water resource managem.
Ad7	Labour Unions
Ad8	Science & Education
Ad9	Administrative bodies

Civil Society (6)

Cs1	Endconsumers
Cs2	General public
Cs3	Regional & local public
Cs4	Neighbours
Cs5	Property owners
Cs6	Citizens initiatives

Press & Media (5)

Pr1	Scientific journals
Pr2	Hydrogen & energy magaz.
Pr3	Nationwide & regional newsp.
Pr4	Social media
Pr5	Public & Private channels

Politics (16)

Po1	Government of Norway
Po2	Goverment of the US
Po3	Government of Russia
Po4	Government of Saudi Arabia
Po5	Government of Iraq
Po6	Government of Algeria
Po7	Government of China
Po8	Government of Australia
Po9	Government of Argentinia
Po10	Government of Spain
Po11	Government of Morocco
Po12	Governments of Sub-Sahara
Po13	Government of Canada
Po14	Government of Chile
Po15	Government of France
Po16	Government of United K.

Associations & NGOs (5)

As1	International energy agenc.
As2	European hydrogen associat.
As3	National gas and water ass.
As4	National climate associatons
As5	Nature conservation ass.

- **No opposing** stakeholders, **57%** as **supportive**, **28%** as **neutral**, **16%** with an **ambivalent** attitude.
- Implementation is highly dependent on the location and the regional or local community.
- **'Neighbours'**, **'Property Owners'**, **'Regional & local public'** require **special attention**.
- Particular attention on **improving knowledge of hydrogen** as an energy carrier.
- Stakeholders ranging from 'Storage operators' to 'Industry', 'Refineries' to 'Energy producers' and 'Grid operators' should be part of **engagement strategies**.

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