Synthesis on major project outcome and proposed implementation plan

Dissemination level: PU - Public

Hystories deliverable D9.2-0

Date: 30 August 2023

The Project is co-founded by European Union

TABLE OF CONTENTS

1. Case for underground hydrogen storage 4
2. Experience and challenges of underground storage of hydrogen 5
3. Hystories project objectives 7
4. Hystories main technology developments (WP1-4) 8
5. Hystories main socio-economic results (WP5-8)......... 13
6. High level conclusions on UHS maturity and insights for UHS deployment.. 17
7. Call for actions 19

7.1. Call for continuity in geological data collection 19
7.2. Call for pilots in porous media 20
7.3. Call for business frames and regulation in Europe 20
7.4. Call for developing storage cost and market requirement insights 21
7.5. Call for actions promoting embeddedness for UHS 22
7.6. Call for standardisation of well equipment.................................... 23

Appendix: Synthesis of the research work packages

1. Case for underground hydrogen storage

Green hydrogen is a clean and renewable energy vector. The use of this gas as an energy source could transform our industry and mobility sustainably. Hydrogen transportation and underground storage infrastructures can enable having this renewable energy available when and where offtakers might call for it, i.e. a usage driven by the demand and not by the production. Hydrogen technologies could be one of the pillars of future European energy and transport systems, making a major contribution to the European Union (EU) transformations to a Net-zero economy by 2050 to its RePower-EU energy independence transition. Underground Hydrogen Storage (UHS) targets salt caverns, depleted hydrocarbon reservoirs, existing gas storage reservoirs, saline aquifers and lined rock caverns. Depleted fields, existing gas storage reservoirs and aquifers were the focus of the Hystories project ("HYdrogen STORage In European Subsurface", see https://hystories.eu/) (Figure 1). The project was funded by the European Union via funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 101007176. It was led by Geostock and ran from January 1st, 2021, to June 30th, 2023. Hystories is made up of seven key public and private partners involved in underground storage in Europe: CO2GeoNet, Fundación para el desarrollo de las nuevas technologÍas del hidrógeno en Aragón (FHa), Geostock, Ludwig-Bölkow-Systemtechnik GmbH (LBST), MicroPro GmbH, Mineral and Energy Economy Research Institute, and Montanuniversitaet Leoben. In addition, 13 industrial operators or suppliers in the gas market were involved as part of the advisory board and 17 third-party entities further enabled the project to gather geological data from 23 European countries.

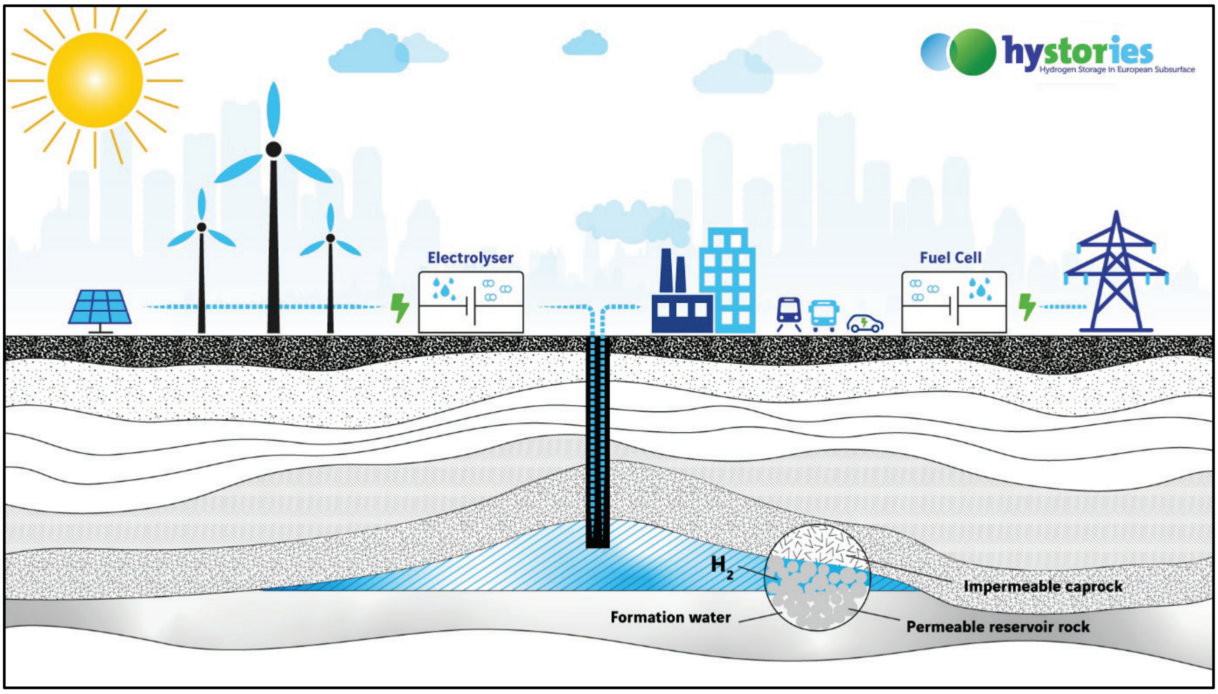

Figure 1: Underground storage of Hydrogen in a porous media (depleted field, aquifer), providing a balance between green Hydrogen production from renewable energy sources and offtakers including industry, residential, mobility or power sectors.

2. Experience and challenges of underground storage of hydrogen

Today, there is only limited industrial experience for pure hydrogen storage:

- 6 historical salt caverns have stored hydrogen for sometimes 50 years, since it started in 1972 in Europe (at Teesside, UK).[1]
- 2 industrial caverns are being leached in Utah (USA). ACES project[2]

Numerous pilot projects focusing on pure hydrogen storage are currently under construction or testing, all of them in Europe[3]:

- 5 in salt caverns (HyStock, Hypster, H2CAST, HyCAVMobil, HPC Krummhörn)
- 1 in depleted field (Sun Storage 2030)
- 1 in lined rock cavern (HyBrit).

When including both storage of pure hydrogen and blends as well, and projects that are not necessarily in construction or commissioning stage, IEA Hydrogen TCP-Task 42 (2023) provides a list of 29 projects. 17 are in salt, 10 in depleted fields, 1 in aquifer, and 1 in lined rock cavern. Out of these 29 projects, all of them are in Europe except the above mentioned industrial UHS in salt cavern projects under construction or operation in the USA, and the Hychico storage blend project in Argentina.

There is historical industrial experience of Town gas storage (a 30 % to 50 % hydrogen blend) in porous media (depleted oil and gas fields, existing gas storage reservoirs and aquifers) but none for pure hydrogen storage. However, since it has similar functional and operational principles for the design and construction of facilities and wells as for the mature natural gas storage industry, it appears intuitive to transfer this knowledge to UHS. Hystories D1.1 presented how ranking of sites based on favourable and unfavourable characteristics in use for natural gas porous storage can be applied. Despite high similarities between natural gas and hydrogen underground storage facilities, there are also significant differences between these two industries:

- In physical and chemical properties of the stored gas:
  - Hydrogen has a higher reactivity which can be catalysed by anaerobic microorganisms.
  - Hydrogen causes embrittlement issues for steel materials.

1 Cf. public detail on these experiences in SMRI RR 2023-1.: Buzogany, R., Bernhardt, H., Réveillère, A., Fournier, C., Voegli, S., Duhan, J. (2023) Hydrogen Storage in Salt Caverns Current Status and Potential Future Research Topics

2 Fernandez, A., Minas, S., Skaug, N., ACES Green Hydrogen Salt Cavern Storage Project. Proc. of SMRI Fall 2022 meeting

3 Cf. summaries of these projects in IEA Hydrogen TCP-Task 42 (2023), “Underground Hydrogen Storage: Technology Monitor Report”, 153 pages including appendices

- Hydrogen has a lower viscosity (creating fingering effects in reservoirs) and energy volumetric density (approx. 3 times more cavern or pore volume is needed to store a given amount of energy).

- On the spatial and time-frame deployment of the industrial sector:
  - A major infrastructure industry should be developed in only a few decades for hydrogen, whereas it took a century for natural gas.
  - This deployment is thought at the European scale from the beginning, whereas it was developed at regional / national scale for natural gas, and then interconnected.
- One is an established industry, the other it yet to be developed:
  - Drivers for storage capacity requirement (supply and offtakes fluctuations) are largely different.
  - As of today, storage needs, in terms of capacity and deliverability, and storage cycles, are hypothetical for hydrogen at industrial scale, whereas they are established for natural gas.
  - As of today, business models for storing are conceptual for hydrogen, whereas they are established for natural gas.
- Development of infrastructures in the 2020s-2040s:
  - Attention to limiting the environmental footprint and gaining the societal embeddedness are key in todays and tomorrows' hydrogen infrastructure deployment; these concerns were different for natural gas infrastructure deployment in the previous century.

3. Hystories project objectives

While storing pure hydrogen in salt caverns has been practiced since the 1970s in Europe, hydrogen storage has not yet been carried out anywhere in depleted fields or aquifers. Although many aspects will be similar to the existing industry of natural gas underground storage, technical developments are still needed to validate this solution, particularly in terms of:

- The bio- and geo-chemical impacts of storage on the subsurface
- The quality of the hydrogen subsequently extracted from the UHS, (contamination due to H_2 contacting the fluids and the rock in the reservoir)
- The identification and ranking of trap candidates at European scale.

Those are the reasons underlying Hystories' 1st strategic objective: to bring technical development to the remaining feasibility questions for the implementation of large-scale storage of renewable hydrogen in depleted fields or aquifers.

Future UHS and transportation network are infrastructure assets which will typically require a decade to develop and will cost billions of euros. Well anticipated planning will be key for future social acceptance and financial security. Hystories has developed insights to inform decision makers in governments and industry who will face these deployment decisions. Those are the reasons underlying Hystories' 2nd strategic objective: to undertake a techno-economic assessment of how the underground storage of renewable hydrogen could facilitate achieving a zero-emissions energy system in the EU by 2050.

These 1st and 2nd strategic objectives correspond to the work identified respectively on the left and right columns of Figure 2 below:

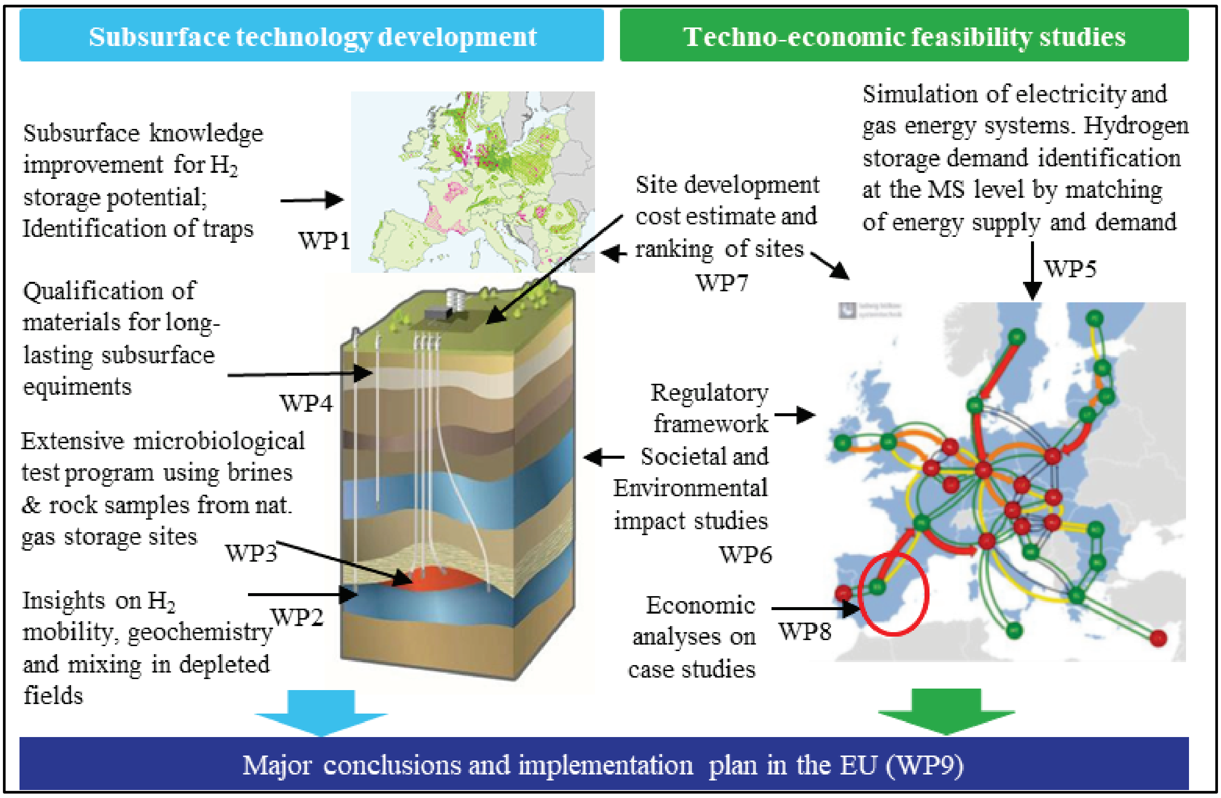

Figure 2: Hystories work program

4. Hystories main technology developments (WP1-4)

Hystories aimed at identifying suitable UHS sites in depleted hydrocarbon fields and saline aquifers both onshore and offshore at a European scale. Publicly available data were analyzed, based on previous related works (most notably results of ESTMAP[4] and CO2STOP[5] projects) and additional data, when possible, notably from well stratigraphy and logs. For instance, 26 traps were identified and characterized, onshore and offshore in Italy, as presented in Figure 3.

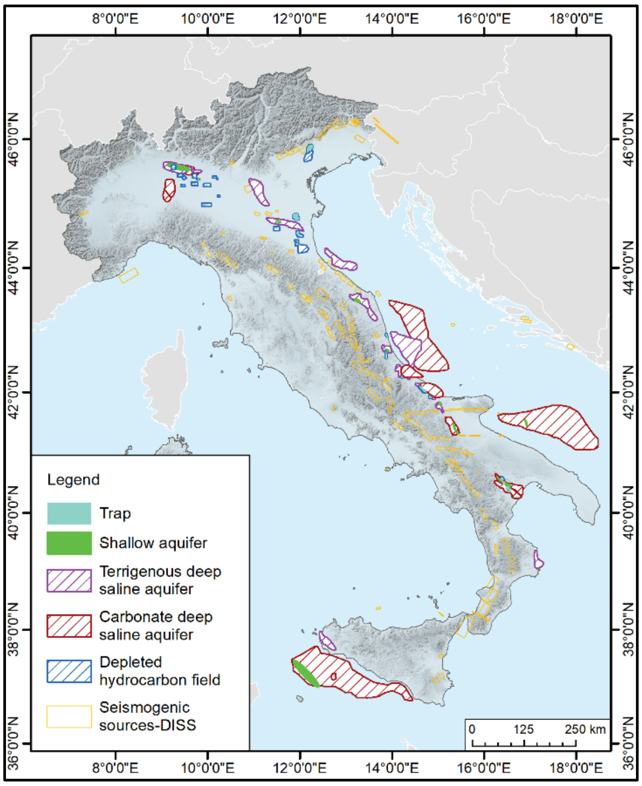

Figure 3. Map of the distribution of the potential UHS site in Italy (Modified from Barison et al., 2023[6])

This work has been done by 17 European geological surveys or research institutes for 23 individual European countries, as presented in Hystories D1.4. Hystories has delivered a **database of European geological hydrogen storage opportunities** collating available geological data on reservoir and seal characteristics for depleted hydrocarbon fields and saline aquifers to support strategic decision making. The database is accessible via a public GIS to highlight regions and sites that may be suitable for development into storage sites for hydrogen, from a geological perspective.

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4 https://energnet.eu/wp-content/uploads/2021/02/3-Hladik_ESTMAP-presentation-Paris-2019-11_for-web.pdf

5 https://setis.ec.europa.eu/european-co2-storage-database_en

6 Barison, E.; Donda, F.; Merson, B.; Le Gallo, Y.; Réveillère, A. An Insight into Underground Hydrogen Storage in Italy. *Sustainability* **2023**, *15*, 6886. https://doi.org/10.3390/su15086886

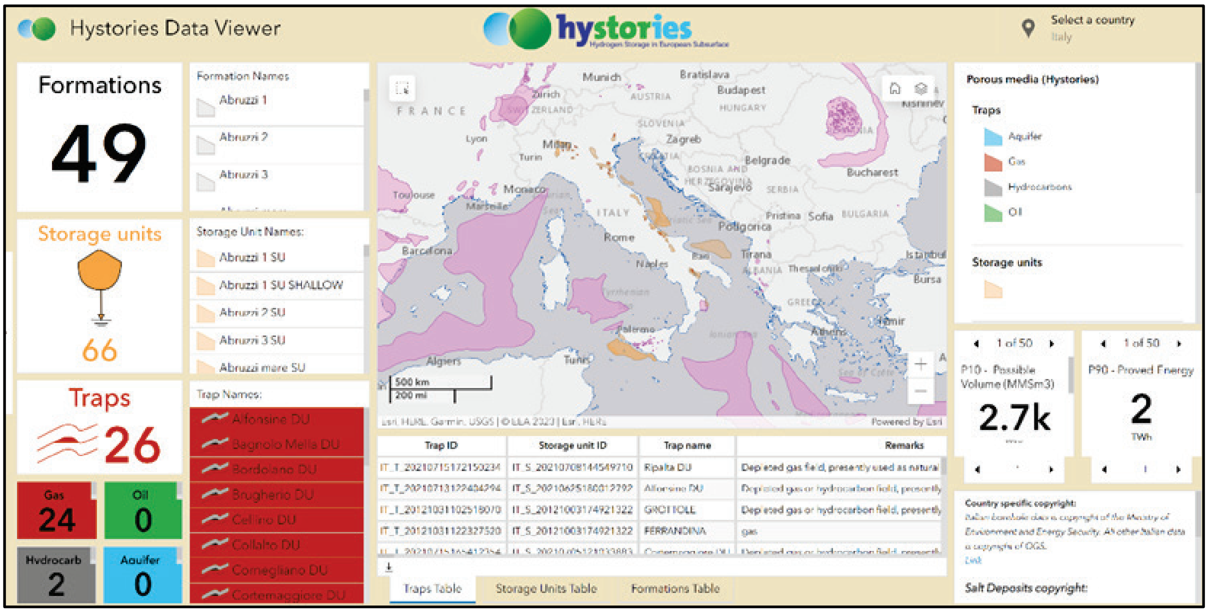


Figure 4: Public GIS visualization of the European scale porous media database for Italy

Based on the information contained in this database, Hystories developed a capacity estimation for 800+ porous traps in EU-27 and 4 neighbouring countries, finding a **total Hydrogen storage resource in depleted fields and aquifers of 6 850 TWh onshore (19 000 TWh with onshore and offshore) (**Hystories D2.2**),** as presented in Figure 5. It was then possible to estimate the possible hydrogen working volume for each country as presented in Figure 6.

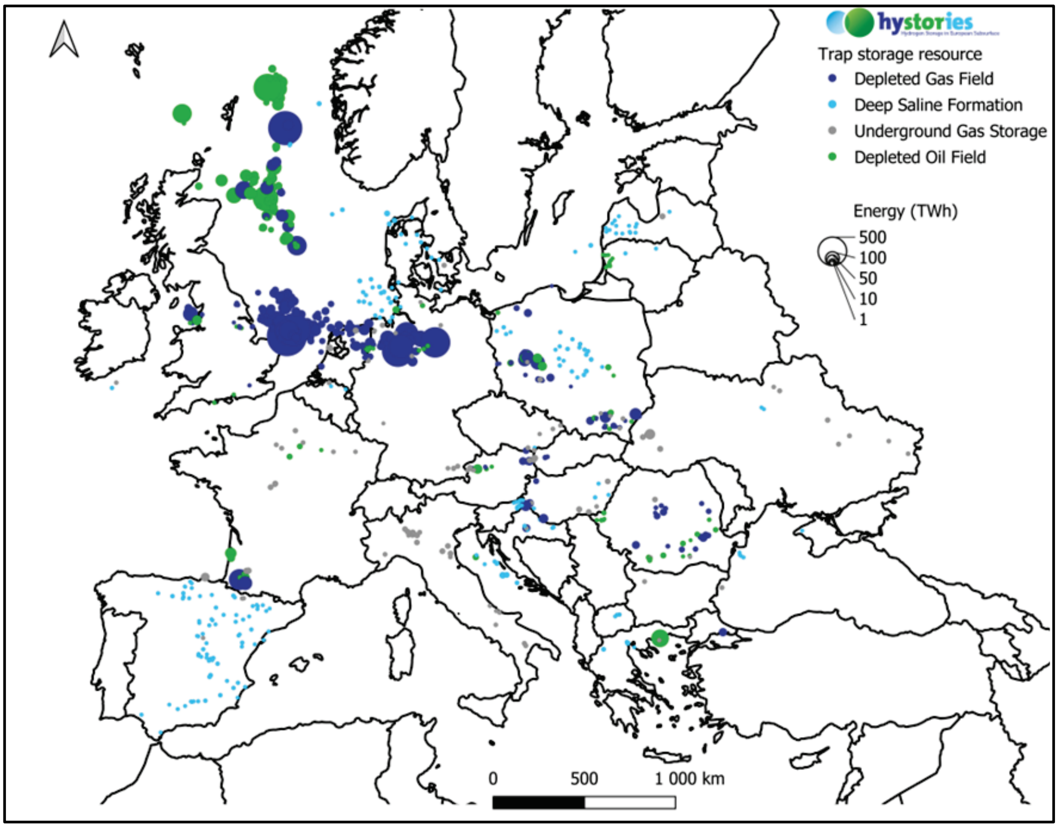


Figure 5: Map hydrogen working storage resource estimation

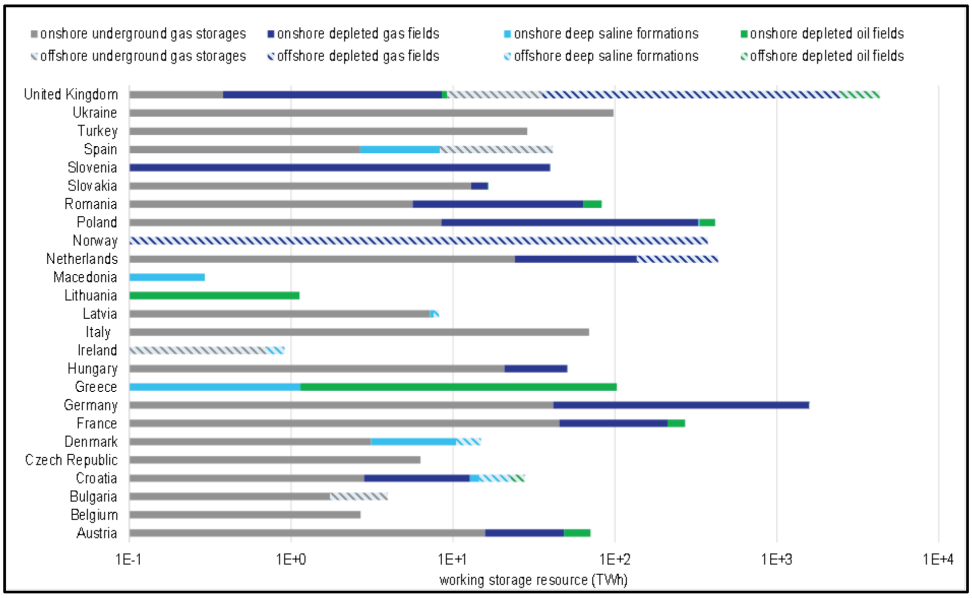


Figure 6: Total hydrogen working storage resources for the different porous media per country

To assess the potential risks associated to microbial activity in future underground hydrogen storages, the formation waters present in eleven storage sites in porous formations in Europe currently used for gas storage have been sampled (downhole sampling), covering a wide range of relevant UHS conditions. These waters were analysed and the present microorganisms were characterized as part of WP3. Hydrogen-consuming microorganisms' groups were found in all but one of these samples. Low and high hydrogen pressure reactivity tests were performed to assess the consumption rate of hydrogen, and specific parameters which could be related to this consumption were looked for. This led to an **operational flowchart to assess the microbial activity risk in UHS** (Figure 7), which uses reservoir characteristics only, a priori available or measurable information.

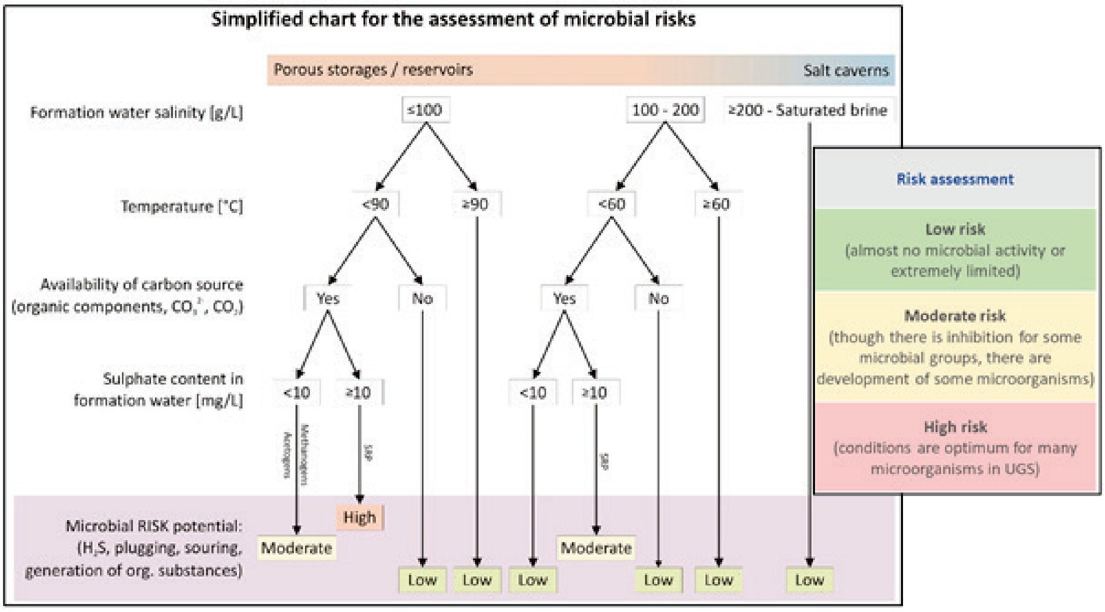


Figure 7: Simplified chart for a risk assessment for UGS based on temperature, salinity, carbon and sulphate availability. From D3.4

Hystories used experimental results and historical industrial town gas experience to **develop geochemical models of the bio-reactivity**, in box models prior to applying them at large scale through 3D models to **assess the expected impacts at operational storage scale**. 0-D and 3-D models were developed on one specific case to predict the kinetics of the reaction at the scale of one storage and during five seasonal cycles of hydrogen injection and withdrawal. It was highlighted that hydrogen consumption was quantified at 5 % after 70 days in the laboratory experiments in this specific case. Using 3D reactive modelling, hydrogen consumption at the end of the 5 seasonal cycles was 0.06 % using the laboratory-scale reactivity, and **0.004 % using the storage scale reactivity** as presented in D3.3.

Hystories **tested a dozen of casing steel grades in hydrogen atmosphere**, under constant or cyclic load conditions, analysed localized corrosion, damage, hydrogen uptake and permeation, and finally assessed their **applicability for storage well conditions (WP4)**. Based on the results of localized corrosion rates and cracking under constant load test, an application overview for investigated materials was presented, as shown on Figure 8. It shall be noted that results observed during Hystories laboratory tests sometimes differ from the assessment found in other public literature. Notably, results obtained in presence of H_2S in Hystories are found to be more conservative.

	Material	Damage	Application with H_2S based on ISO 15156	Applicability in H_2 environment
increasing yield strength	20MnV5	no damage	Not specified	well applicable
	welded J55	no damage	Acceptable for H_2S application for all temperatures	well applicable
	welded J55 pre-corroded	no damage		
	welded J55 with notch	no damage		
	K55	no damage	Acceptable for H_2S application for all temperatures	well applicable when localized corrosion is not an issue
	K55 pre-corroded	no damage		
	K55 with notch	some localized damage		
	welded K55	no damage	Acceptable for H_2S application if hardness ≤ 22 HRC	well applicable
	L80	deep localized damage	Acceptable for H_2S application for all temperatures provided that it is type 1	applicable when localized corrosion is not an issue
	L80 pre-corroded	some localized damage		
	L80 with notch	some localized damage		
	P110	deep localized damage	Acceptable for H_2S application only if T° > 80°C	applicable at RT when no H_2S is present
	quenched material	failure in H_2	Not applicable	not applicable
increasing alloy content	13%Cr	no damage	Acceptable if pH_2S < 10.2 kPA	well applicable
	316L supplier 1	no damage	Acceptable if pH_2S < 10.2 kPA	well applicable
	316L supplier 2	no damage		well applicable
	Duplex 2205	failure in (H_2 + CO_2 + H_2S)	Acceptable if pH_2S < 2 kPA	not applicable
	Alloy 625	no damage	Acceptable for H_2S application for all temperatures	well applicable

**no damage **localized damage **failure

**well applicable in hydrogen environment **applicable in hydrogen environment when localized corrosion is not an issue **not applicable in hydrogen environment

Material	Hystories results	ASME B31-12	ISO/TR 15916	NASA/TM-2016-218602	MR0175 / ISO 15156
20MnV5	Well applicable	Acceptable as carbon steel	/	/	/
J55	Well applicable	Acceptable as carbon steel	/	/	Acceptable for H_2S application for all temperatures
K55	Well applicable when localized corrosion is not an issue	Acceptable as carbon steel	/	/	Acceptable for H_2S application for all temperatures
L80	Applicable when localized corrosion is not an issue	Acceptable as carbon steel	/	/	Acceptable for H_2S application for all temperatures provided that it is type 1
P110	Applicable at RT when H_2S is not present	Acceptable as low alloy steel	/	/	Acceptable for H_2S application only if T > 80 °C
13% Cr (410)	Well applicable	/	Severely embrittled	HEE extreme	Acceptable if pH_2S < 10.2 kPa
316 L	Well applicable	Acceptable	Slightly embrittled	HEE negligible	Acceptable if pH_2S < 10.2 kPa
Duplex 2205	Not applicable	/	/	/	Acceptable if pH_2S < 2 kPa
Alloy 625 (Inconel 625)	Well applicable	Not acceptable	/	HEE high	Acceptable for H_2S application for all temperatures

Figure 8: Applicability of investigated steels according to results of Constant Load Tests (left, from D4.6) and comparison with classifications found in the literature (right, from D4.7)

Moreover, risk associated to hydrogen embrittlement depends on the environment: presence of impurities in the gas, electrolyte, existence of dynamic or constant external stresses. A chart (Figure 9) is proposed to select a material for a hydrogen storage well depending on its environment:

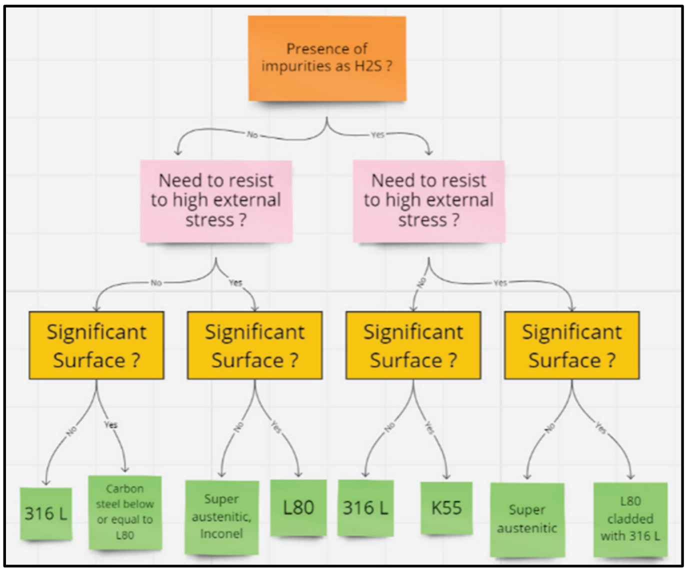


Figure 9: Proposed material selection flowchart for wells in hydrogen environment (gas). This list of materials is not exhaustive and other alternatives could be proposed. From D4.7

5. Hystories main socio-economic results (WP5-8)

The regulation readiness for UHS was assessed based on surveys of stakeholders launched in 2021, showing that it was developed or under development for 6 of the 17 European countries reviewed (Table 1, WP6). Detailed procedures were summarized for France, Germany, Poland and Spain. (Hystories D6.1).

Table 1: Conclusions of the September 2021 UHS legal framework review, from D6.1.

Current legal framework	Country
Legislation in force to UHS	Austria[1], Denmark, Germany[2], UK[3]
UHS legislation is under development	France, Netherlands
No UHS legislation under development	Czech Republic, Estonia, Greece, Hungary, Italy, Latvia, Lithuania, Poland, Portugal[4], Romania, Spain[4]

1 Only for scientific research
2 Legislation in force for underground storage of chemical product, not specific UHS
3 Long operation experience
4 UHS named in national strategy

A reference assessment for 7 impact categories (including climate change) of a salt cavern or porous media UHS over its life cycle shows that **the main environmental footprint derives from the use of electricity during operation** (Figure 10):

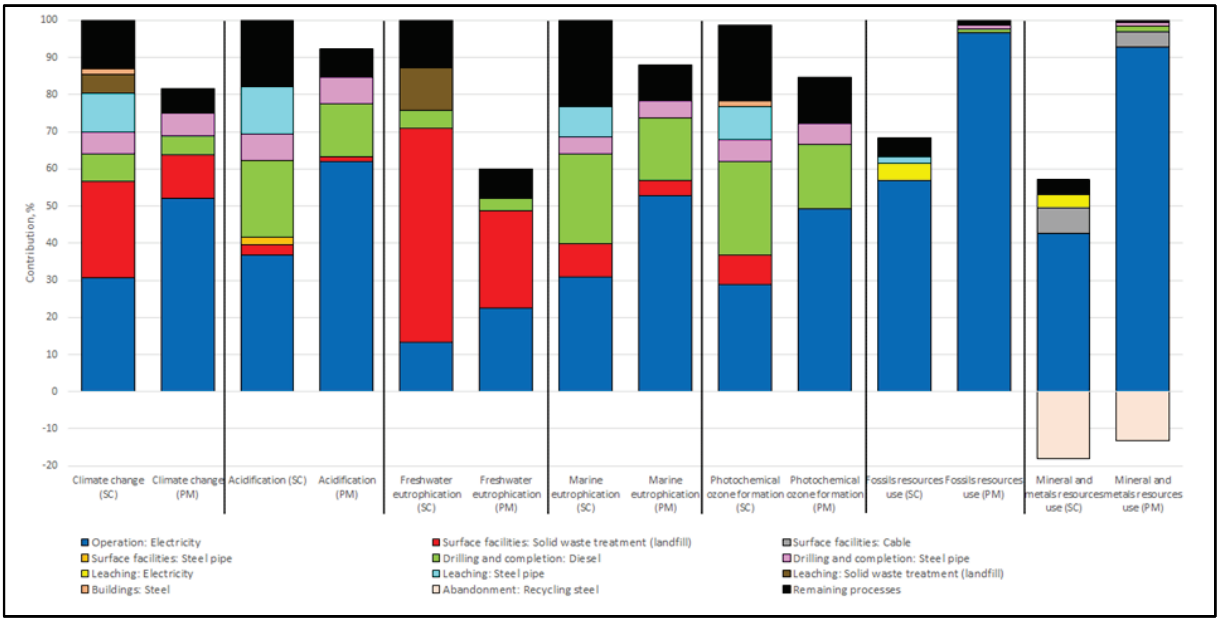
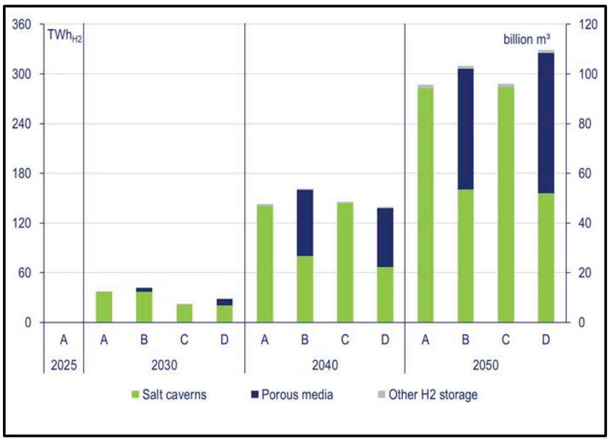


Figure 10: Contributions of main processes of salt cavern (SC) and porous media (PM) by impact category. From D6.3

Using a Social Impact Study, UHS' perception was analysed by a survey of general public in three countries. It suggested possible "Not in My Backyard" syndrome. In addition, a survey of stakeholders involved in presumably several hundreds of projects altogether found that two experienced projects affected by public pressure (Hystories D6.4)

A comprehensive energy system modelling was performed for EU27+UK in WP5. In total, four scenarios were developed (see D5.1) and analysed considering (a) different H_2 production pathway (domestic production vs. imports from non-EU regions) and (b) different H_2 storage technologies (salt caverns, storage in porous media and other aboveground H_2 storage possibilities). The results confirmed the pivotal role of hydrogen technologies in a future energy system with high shares of renewable energy sources – especially for achieving long-term decarbonisation targets. **Significant UHS capacities are already needed in the short-term until 2030 with 20 - 40 TWh_{H2} (or 7 – 14 billion m³)**, including mainly salt caverns but also first porous media sites. **In the long term after 2030, the required storage volume capacities in the scenarios substantially grow up to more than (300 TWh_{H2} or 100 billion m³ in 2050) with an equal split between salt caverns and porous media.** The capacities strongly depend on the overall hydrogen demand (1,700-1,900 TWh/a in 2050) both from different end-use sectors (industry, mobility and heating accounting for up to 90 % of total demand) and from power sector (i.e. re-electrification). Although potential storage capacities for pure hydrogen might be lower on TWh-basis in comparison to today's conventional natural gas (ca. 1,000 TWh_{CH4}), the need for geological reservoirs will be similar due to lower volumetric density of hydrogen. Moreover, both natural gas and hydrogen storage have a similar **ratio between volume capacity and demand of around 15-20 %**. Due to long lead times of underground hydrogen projects of up to 10-12 years (incl. planning), this underlines the urgent need for building sufficient capacities in time.



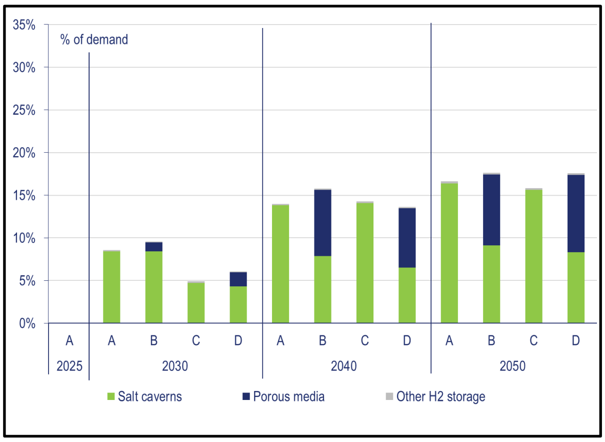


Figure 11: Optimal storage volume capacity in absolute values (left) and as percentage of overall hydrogen demand (right) in EU-27 & UK (Source: D5.5-2)

These **storage demand figures are orders of magnitude less than the estimated UHS capacities of 6 720 TWh in onshore porous storage resources (Hystories result) or 13 800 TWh in salt caverns (public result)** in EU-27+UK (Figure 12):

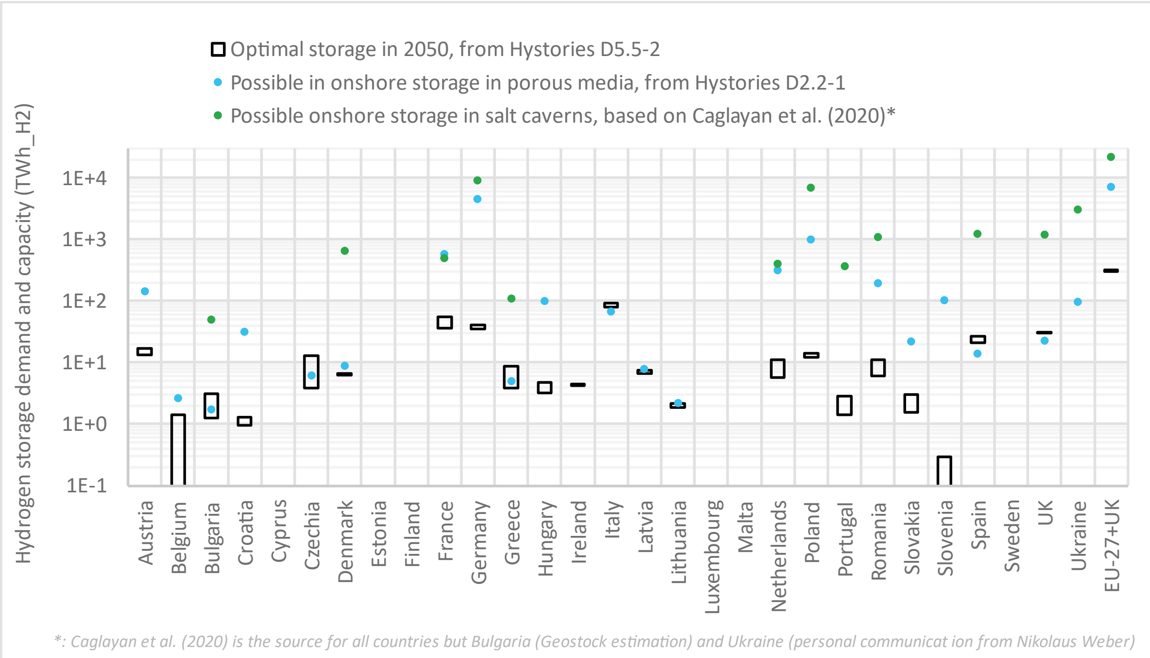


Figure 12: Optimal storage capacity in EU-27+UK+Ukraine in 2050 (scenarios B and D of WP5) and technically possible onshore storage capacity in Porous Media and Salt caverns. From D7.3-1

This implies a **need for ranking the possible underground hydrogen storage sites in Europe**, which was performed in WP7. The cost for an underground storage is dependent on site-specific characteristics and on the cycle the storage shall operate. A typical design of an integrated UHS, including surface facilities necessary to operate it, has been developed for three capacity/withdrawal flowrate scenario (Hystories D7.1) and used to develop a bottom-up cost model with properly defined boundary limits (Hystories D7.2). This model is parametric, hydrogen-specific and allows a full lifecycle cost assessment, including development, construction, commissioning & start-up, operation & maintenance and abandonment. It was applied for the fast and seasonal cycles found by the energy modelling (WP5) to 800+ porous traps, 18 bedded salt deposits and salt domes, all of them onshore UHS candidate sites in Europe (Hystories D7.3). Matching the 2050 storage demand with the most economic sites with either of these technologies leads to an estimation of the Levelized Cost of Storage (LCOS) of 1.1 €/kg (seasonal) or 2.6 €/kg (fast cycles) in porous media, and 2.3 €/kg (seasonal) or 2.0 €/kg (fast cycles) in salt caverns.

In the renewable hydrogen supply chain at European scale, including production, transportation and storage, UHS applies to only around 15 % of the overall hydrogen demand. UHS would therefore contribute to $LCOH_{Storage}$, part of the Levelized Cost Of Hydrogen[7], of about 0.16 €/kg (seasonal) or 0.39 €/kg (fast cycles) in porous media, and 0.34 €/kg (seasonal) or 0.30 €/kg (fast) in salt caverns.

7 $LCOH = LCOH_{production} + LCOH_{transport} + LCOH_{storage} + LCOH_{other}$. Cf. for instance D5.5-2

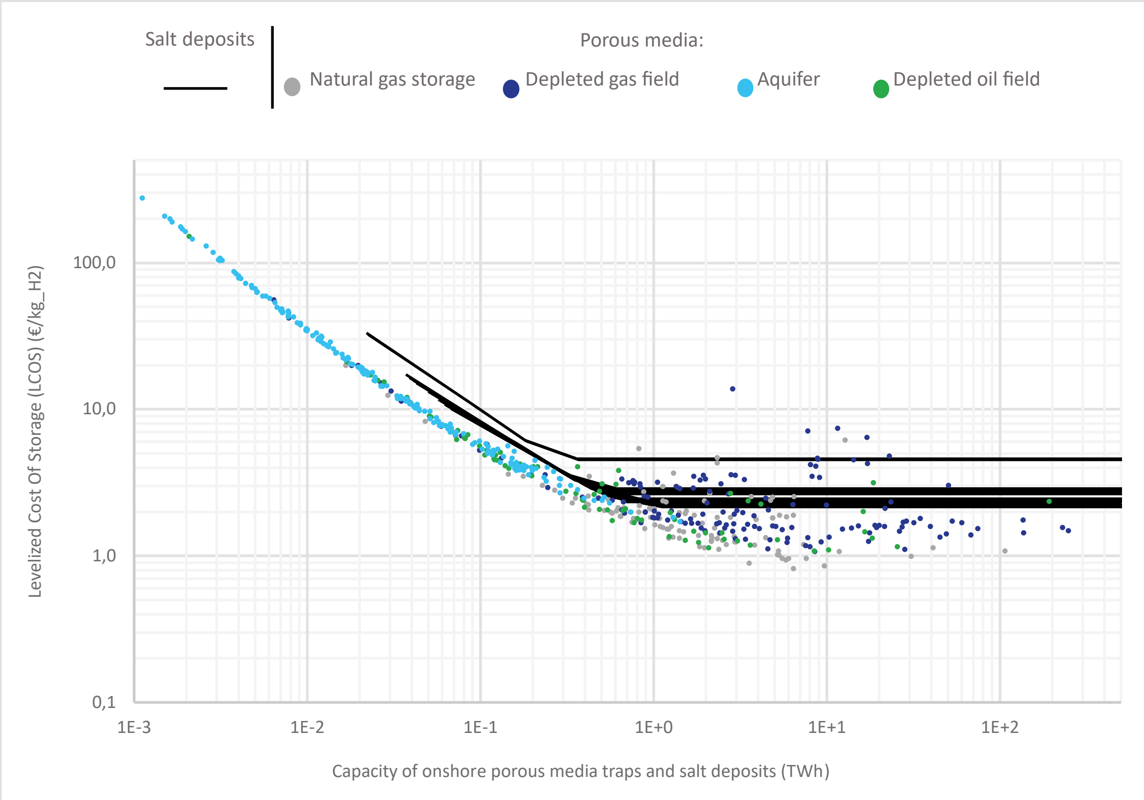


Figure 13: LCOS for onshore porous media and salt caverns in EU-27+UK+Ukraine, seasonal cycle, per capacity. For porous media (dots indicate the maximum capacity of the trap) and for salt caverns (size to be chosen by design on the solid line). From D7.3-1

A suitability mark reflecting relatively higher readiness and lower technical risk, was also estimated for porous media traps and salt caverns. It resulted in **higher suitability marks for salt caverns, and then for the existing natural gas storages and depleted gas fields, making it the preferred options for UHS with current knowledge.**

Case studies for specific UHS sites in France, Germany, Italy, Poland and Spain in WP8 enabled a more detailed look at the implementation of UHS projects, notably by assessing economic opportunities under different regulatory and economic framework conditions and identifying most relevant business case-related factors. However, detailed case-specific analysis will be required taking individual project characteristics into account.

6. High level conclusions on UHS maturity and insights for UHS deployment

Hystories high level assessment of the maturity of UHS is the following:

- Hydrogen Storage in salt caverns is seen as technically mature, notably owing to the 50+ years of industrial experience and to the low risk related to microbiological activity. However, technical development is a continuous process and is desirable for several components of the technology[8].
- No obvious technical showstopper is foreseen for Hydrogen storage in depleted fields or aquifers. However, the purity upon withdrawal (due to microbiological activity and possibly mixing), gas treatment costs and further H_2 grid specifications may affect this deployment.
- Storing 5 % to 18 % of the hydrogen demand in UHS is an important pillar for system flexibility and thus security of supply: the need of H_2 storage is forecasted to increase strongly after 2030 due to large H_2 demand and substantial share of intermittent power in hydrogen generation. The value of the UHS of renewable hydrogen within the entire value chain can be interpreted as the share of storage cost in overall H_2 cost. Its overall cost accounts for up to ca. 15 % of the overall H_2 supply chain costs in the long-term. In any case, this level of UHS is cheaper than alternative flexibility options. This economic interest calls for hydrogen infrastructures operational as early as in 2030, which would require investment decision being taking now. But business frame that would enable industrial projects to develop are not mature to date in Europe. Solving “chicken and egg” problem is one of the most significant issues.

Hystories technical and socio-economic results already provide key knowledge and insights for supporting UHS deployment, as presented in the previous sections 4 and 5.

A number of these results have already been used to derive the Levelized Cost Of Storage (LCOS) and Suitability Mark presented in D7.3. In addition to these, assessing the opportunity of UHS development also requires on the location and proximity to foreseen hydrogen pipelines. Hystories developed a storage opportunity map providing practical insights on cost, storage capacity and suitability mark to guide public and private actors in their decisions for identifying promising future storage solutions (aquifer, depleted field, salt cavern) (Figure 14):

8 Salt cavern technical development were not the focus of Hystories. SMRI report RR2023-1, by Buzogany et al. 2023, provides a clear industrial view on the gaps to date.

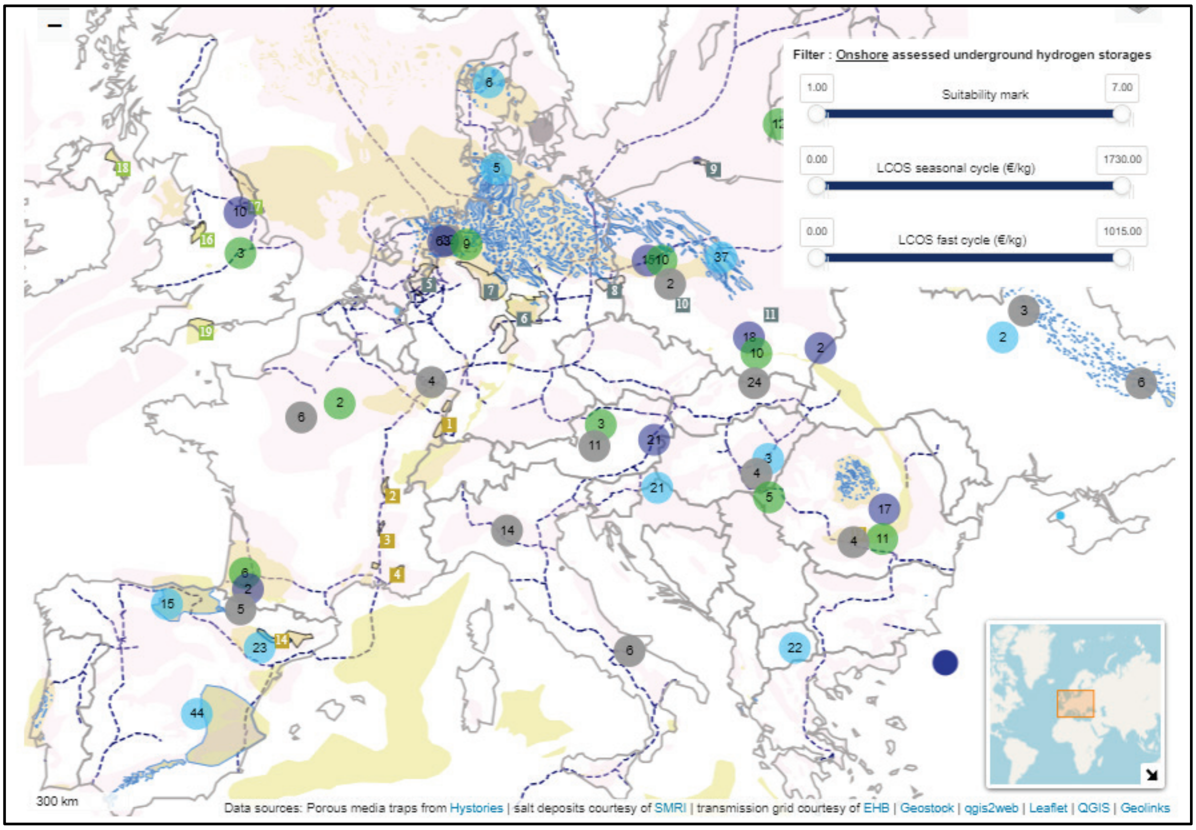


Figure 14: Hydrogen storage opportunity map, from www.hystories.eu/map

7. Call for actions

The following sections present the overarching recommendations that are considered key to enabling UHS deployment.

7.1. Call for continuity in geological data collection

The Hystories geological database contains data available in the public domain and therefore the absence of identified storage potential does not necessarily indicate an absence of opportunity. The number of aquifers may look low when compared to the depleted fields: this does not directly reflect the number of traps existing in European subsurface, but the number that are publicly identified. A structural trap in an aquifer is essentially unknown until there is enough geological and geophysical characterization to support there is one. The Hystories database is therefore far from including all existing traps in European Subsurface. Regarding the number of depleted fields, there is a need for public data release in some countries.

Call for actions :

- Build on Hystories database work to continue this first porous trap data collection dedicated and focused on Hydrogen storage.
- Set a European frame to have a reference database that has to be improved whenever additional geological data is publicly released from new or historical exploration.
- Complete the data parameters for available traps. Complete the number of formations, units and traps in the database.
- Expend the database geographical scope.
- Including not only the SMRI salt deposits (which can be seen as similar to the "formation" shape for porous media), but the areas where storage cavern is a priori technically feasible (which would be closer to the porous media "traps").
- Expend the database scope by including suitable rock for lined rock caverns.

7.2. Call for pilots in porous media

As presented in section 2, as of today, there are 2 ongoing industrial H_2 caverns being developed (in the USA), and 8 storage pilots recently commissioned or under construction in Europe, among which 5 are in salt caverns, 1 in depleted fields, 1 in lined rock cavern. For 2023, the IEA Clean Technology guide[9] assessed the technology readiness for pure hydrogen storage in depleted fields and aquifers as significantly lower than for salt caverns (Technology Readiness Levels of respectively 5, 3 and 9-10). Demonstrating the feasibility for hydrogen storage in depleted fields and aquifers is of great interest nowadays, as it can be a very appropriate technology to store large quantities of hydrogen. Impact of mixing and microbial conversion of hydrogen on the gas quality are of particular interest and would require gas quality observations on pilot or industrial scale over long time periods.

Call for actions:

- Promote pilots for pure hydrogen storage in depleted fields and aquifers.
- Assess, possibly over 10+ years, the impact at scale of gas microbial conversion on the withdrawn gas quality.
- Assess the transport behaviour within the porous media: flow, containment and mixing of hydrogen with other gases.

7.3. Call for business frames and regulation in Europe

Even though UHS in salt caverns is seen as technically mature, there are only pilot scale developments in Europe today, whereas there are 2 industrial scale hydrogen caverns under leaching and no pilot in the USA. The lack of viable business case for project developers in Europe is likely part of the explanation. Pilots are key to guarantee a fast ramp-up of available UHS capacity (up to 20-40 TWh by 2030) in line with the development of a trans-European hydrogen transport infrastructure until 2030.

Call for actions:

- Adoption business frame that can reduce investment risks of early UHS industrial projects.
- Investigation of options for regulation frames that can secure long term industrial deployment.
- Investigation of legal frames for strategic storage purpose (cf. oil storage experience)
- Ensure that the permitting and legal frame is in place to enable hydrogen storage development in each country.

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9 on 01/08/2023

7.4. Call for developing storage cost and market requirement insights

In order to capture the role of underground hydrogen storage, the value it brings to the system has to be established in terms of location, storage capacity (working gas), deliverability (withdrawal flow rate) capacity, operating cycles (number of full cycles equivalent per year). The cost for providing such service has to be estimated in a reliable way. Estimates of expected UHS demand between 2030 and 2050 have been established in Hystories, and many countries have also published their own estimations. These UHS demand estimations are based on a set of hypotheses that are still uncertain. Hystories also developed fairly reliable and integrated CAPEX and OPEX cost model, H_2-specific and parametric for new UHS in salt caverns and porous media, based on mature underground storages engineering experience. Concrete feedback from UHS development and technology providers is still lacking. Comparison with other public sources show large differences in numbers, suggesting the inherent variability and project-specific character of cost estimation for UHS – and also its complexity.

Call for actions:

- Enhance publicly available UHS cost estimations, notably:
    - Further efforts are needed to design and cost estimate the gas treatment process for UHS in porous reservoirs (which notably depends on future gas grid injection specifications)
    - Include feedbacks from the emerging pilot and industrial UHS experience
    - Publish cost model for very small, or large, porous media or salt cavern projects.
- Publish cost estimations for conversions of existing assets (e.g. natural gas storage) and of reuse (e.g. depleted gas fields, existing salt caverns in brine).
- Assess criticality of UHS from a holistic perspective taking their different values into account, e.g. with regard to security of energy supply (national and European in the frame of REPower-EU) as well as their role for successful ramp up an integration of intermittent renewable energies. Account for externalities such as supply disturbances, geopolitical developments, and global hydrogen market developments.
- Refine the spatial grid to capture local, regional, hydrogen valleys early deployment opportunities and also take grid limitations and congestions into account.

7.5. Call for actions promoting embeddedness for UHS

Achieving successful deployment of Underground Hydrogen Storage (UHS) hinges on reaching a commendable level of societal embeddedness. To foster this essential acceptance, proactive steps must be taken. This entails transparently sharing information, particularly regarding pilot projects, to demystify the technology and build trust. Equally vital is the active engagement of stakeholders and the public in decision-making processes. By involving the broader community, addressing concerns, and showcasing the benefits, it will be possible to pave the way for the seamless integration of underground hydrogen storage in porous media and salt caverns. In ensuring the widespread acceptance of UHS, conducting meaningful public consultations with local communities holds paramount importance. These consultations effectively address the "not in my backyard" phenomenon, fostering mutual understanding and collaboration. The study conducted within the Hystories project underscored the existing baseline understanding among the general public. However, it also revealed a crucial gap in comprehending hydrogen technologies, which lags behind other established sustainable alternatives. Thus, actively disseminating information and insights regarding hydrogen technology's development is pivotal for bridging this gap, propelling broader support and ushering in a sustainable energy future.

Call for actions:

- Sharing of information on UHS and pilot projects
- Involvement of stakeholders/public
- Conduct public consultations fostering local cooperation
- Intensify educational campaigns on sustainable energy sources, storage technologies, and climate change, elevating public awareness
- Draw insights from the Hystories project, addressing the disparity in understanding of hydrogen technology compared to other renewables
- Collaborate with educational institutions and media to promote a comprehensive understanding of UHS benefits and mechanics
- Establish open forums for dialogue between experts, policymakers, and the public to address concerns and share progress transparently
- Develop localized case studies showcasing successful UHS integration, bolstering confidence in its viability.

7.6. Call for standardisation of well equipment

Available standards for the selection of suitable steel grades for hydrogen application are available for surface facilities or pipeline systems. Technical standardization is not yet available for UHS application. Based on related industrial experiences and standards, and on recent H_2-specific research results (including by Hystories), it can be concluded that suitable materials are available and a flowchart to select them was proposed in Hystories based on environment-specific conditions. However, this mostly focuses on the casing itself, and is not a standardization yet.

Call for actions:

- Complement Hystories experimental program with less conservative conditions regarding H_2/H_2S blends, using a lower partial pressure of H_2S,
- Develop technical standards with regards to steel grades for UHS application,
- Further research and development in the area of welding and connections, elastomers, well equipment (wellheads, packers, subsurface safety valves) for underground hydrogen service,
- Develop procedures for re-qualification of existing wells.

APPENDIX 1

Synthesis of the research work packages

Appendix - Synthesis of the research work packages

Dissemination level: PU - Public

Hystories deliverable D9.2-0 - Appendix

Date: 13 October 2023

The Project is co-founded by European Union

D9.2 APPENDIX TABLE OF CONTENT

1. Foreword 3

2. Synthesis of the research work packages 4

2.1. Work Package 1 - Geological assessment.. 4

2.2. Work Package 2 - Reservoir engineering and geochemistry.................. 8

2.3. Work Package 3 - Microbiology.. 13

2.4. Work package 4 - Material and Corrosion 31

2.5. Work package 5 - Modelling of the European energy system 36

2.6. Work package 6 - Impact studies 41

2.7. Work package 7 - Ranking of geological sites 49

2.8. Work Package 8 - European Case Studies 57

3. Hystories work package within the State of the Art.... 60

4. References 63

1. Foreword

This appendix to the Executive Summary D9.2 is intended to give an overall understanding of the project work by summarizing how it has been conducted in a single document. It does not include any new technical development when compared to Hystories deliverables, referred to as "Dx.y" in the present Appendix. These deliverables are the main reference for each piece of work, and reference to an individual piece of work should refer to them.

2. Synthesis of the research work packages

2.1. Work Package 1 – Geological assessment

Task 1.1 Definition of screening criteria and new H2-relevant parameters

The aim of this task was to identify a set of parameters to be used to characterise possible aquifers and depleted hydrocarbon fields in terms of their potential for H2 storage. A technical workshop was held early during the project (21/01/21) to agree on the main parameters for inclusion in the database. Partners from all work packages that depend on the outputs of WP1 were invited (WP2,3,5). A deliverable, '*D1.1 Definition of Selection Criteria for a Hydrogen Storage Site in Depleted Fields or Aquifers'* was prepared and sets out the first set of Hystories hydrogen storage site screening criteria, mostly based on experience from natural gas underground storage.

Building on D1.1 and following this WP1 first technical workshop, an internal *Screening criteria and database attribute discussion document* was prepared to set out the database structure and parameters. It recorded discussions on parameters to be collected during Hystories, and relied on the unique experience of CGEO for capacity estimation built on CO_2 geological storage, and capability to gather geological knowledge at the European scale. H2 specific criteria were included based on discussions during the technical workshop (21/01/21) e.g. the presence of iron and sulphate.

Additional CO2GeoNet Members and subcontractors from Slovenia and Ukraine joined the WP1 team to offer improved coverage of Europe and a better overview of the European potential. By the end of the project, Hystories offered data from 23 countries, an increase from the 21 countries announced in the proposal and Grant Agreement.

Task 1.2 Development and population of Hystories database of potential stores (oil and gas fields and aquifers)

The aim of this activity was to collate data and information on H_2 storage options onshore and offshore in depleted gas / oil fields and aquifers in Europe. The database was designed based on experience from previous projects on collating heterogeneous data. The database is hierarchical, so the traps are within the storage units which are in within the storage formations, this accommodates the varying levels of data availability. Data were provided from the CO_2StoP and ESTMAP projects (which assessed CO_2 storage and energy storage respectively) as a starting point. These data were verified, and the database expanded with new data by the Hystories partners.

The potential stores which had a well-defined area and more geological data are of particular interest, the Hystories partners collated 965 of these potential stores ("traps"). The output of T1.2 is a unified database of potential stores in Europe (D1.2) which includes 311 geological rock formations that could be suitable for storage, 581 storage units and 965 traps collated by the Hystories partners. As the quality check was ongoing at the end of RP1 and early in RP2, D1.2 was delivered in March 2022. An additional quality check and complementary information were provided by WP2 during storage capacity assessment.

Task 1.3 Geographic Information System (GIS)

The aim of this activity is to display the up-to-date Hystories geological data relevant to H_2 storage in Europe, to include maps of the natural subsurface salt deposits throughout Europe gathered by Horvath et al. (2018) for the Solution Mining Research Institute (SMRI) along with capacity estimates from WP2 (Figure 1).

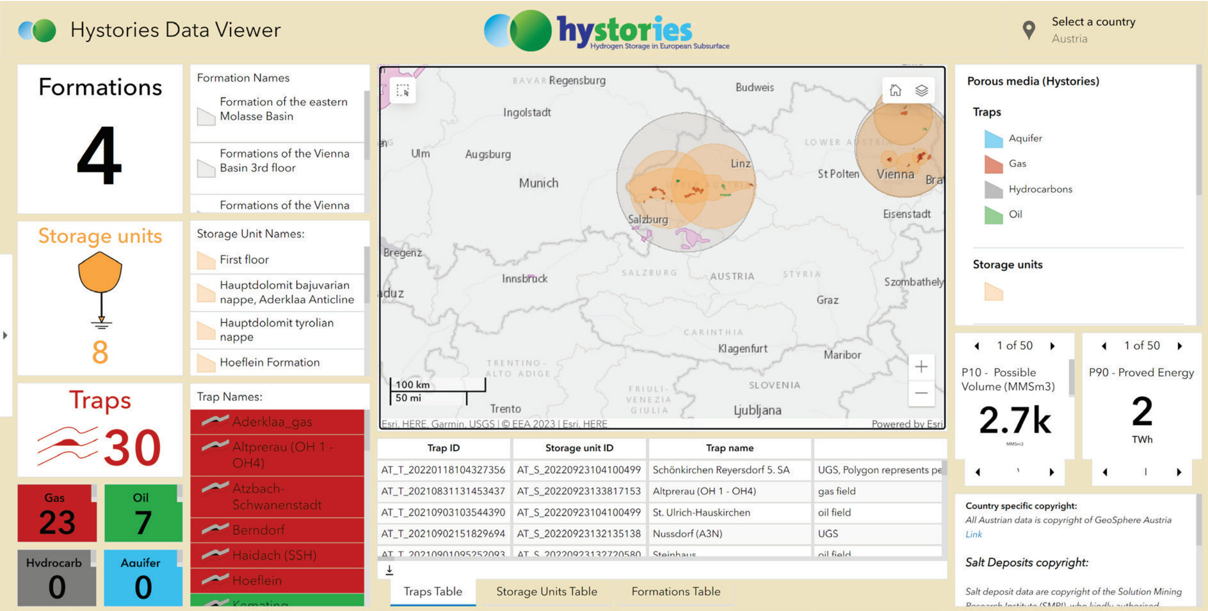


Figure 1: Hystories online portal to the database for Austria

The Hystories Geological GIS will act as a portal to the data stored in the Hystories database. The polygons for display in the GIS have been collated and updated by WP1 partners during Hystories and a GIS to display these data was built during RP2 and is hosted as an ESRI® Arcgis™ interactive map by CGEO-BGS[1]. Users with other GIS software brands can load in the shapefiles which can be downloaded from the online GIS. The shapefiles will be made available via the Hystories website so external partners can also use the data within the terms of the Hystories copyright statement as indicated in the side panel with acknowledgements and references is also shown in Figure 2. This task required multiple interactions between CGEO-BGS and all WP1 parties to ensure consistency of the data offering.

When the GIS was compiled, some data collated during CO_2StoP project were added to increase the coverage of the Hystories database by adding data from additional countries. The updated Hystories database then contained 386 formations, 665 units, and 1136 traps. An additional quality check and complementary information were provided by WP2 during storage capacity assessment. The CO_2StoP data from countries not assessed during the

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

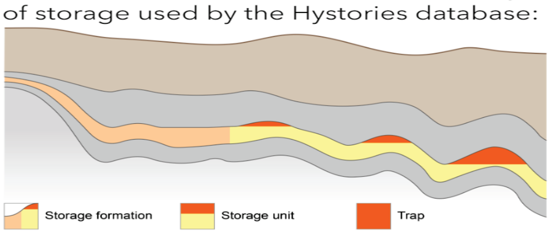
Hystories project were given a quality check but have not been verified or updated by the Hystories project.

About Hystories

The Hydrogen Storage in European Subsurface (Hystories) project addresses the main technical feasibility questions for subsurface storage of green hydrogen as an enabler to help meet climate targets. The main deliverable from workpackage 1 was a unified database collating available geological data on reservoir and seal characteristics for depleted hydrocarbon fields and saline aquifers to support strategic decision making. The database is accessed via this GIS to highlight regions and sites that may be suitable for development into storage sites for hydrogen, from a geological perspective. This GIS only displays data available in the public domain and therefore the absence of identified storage potential does not necessarily indicate an absence of opportunity.

The Hystories database

The primary data included in the desktop and web GIS are the three-level hierarchy of storage used by the Hystories database:



- Storage formations (rock bodies which may have suitable reservoir properties)
- Storage units (parts of the storage formations which have promising reservoir properties)
- Storage traps (parts of storage units that should locally contain hydrogen; hydrocarbon fields or mapped geological closures) Data is added in the following order to the database; first a storage formation is added, then the storage units that fall within that formation. Storage traps, which fall within each storage unit are then added, where data are available.

Click on the layer selection in the map to enable the Salt deposits layer supplied by SMRI alongside the Porous media layers.

Reference and copyright

Reuse of Hystories data is authorised, provided that the "Hystories" project is acknowledged, and the copyright of data are acknowledged as per the statements for each country.

External data: SMRI has kindly allowed display of their salt deposits layer. These data remain the property of SMRI and cannot be reused under the Hystories data reuse statement.

Coastline data © EEA 2021

Capacity estimation data: Porous media trap capacity estimates are based on GIE Storage database published on 14/07/2021 for existing natural gas storages, or are Hystories' own estimation derived from collated geological data for other porous traps. Computation details are given in Hystories report D2.2-1_3D Multi-realisation simulations for fluid flow and mixing issues, please refer to this report for methodological details.

Acknowledgements

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.

Clean Hydrogen Partnership

co-funded by the European Union

Figure 2: Hystories copyrights, acknowledgements and references in the online portal to the database

Task 1.4: Review of regional potential for geological storage

A report '*D1.4 Opportunities in Europe for geological storage of hydrogen in depleted hydrocarbon fields and saline aquifers'* was prepared to accompany the database and GIS to provide an overview of the geological assessment. The report describes how the database and GIS are structured, summarises the data collated during Hystories, and then provides chapters summarising the results from each country involved in Hystories. D1.4 summarises the work carried out in and in particular, the geological context, the data gaps and the storage opportunities assessed on a country-by-country basis.

Achievements and impact for WP1:

WP1 plays a key role in Hystories and interaction with the other WP is a key part of the project activities. The following key achievements and impacts were generated:

- Geodata is key in making strategic decisions on the role for the subsurface in meeting energy and climate demands. Having access to data and the knowledge on how to process, manage and manipulate this data will have a wide-ranging impact on the capacity for strategic decision making.
- Where geological data are available in the public domain, it is possible to identify opportunities where the subsurface could play a role in meeting climate targets. An absence of identified traps does not necessarily indicate an absence of storage potential.
- The wealth of data collated during the Hystories project indicates that there is significant potential for geological storage of hydrogen in depleted hydrocarbon fields and saline aquifers across Europe

Potential storage traps identified through Hystories require further investigation to confirm site suitability for hydrogen underground storage. Development time will vary as detailed and site-specific data need to be acquired, either purchased or collected.

2.2. Work Package 2 - Reservoir engineering and geochemistry

2.2.1. Fluid flow and mixing

Based upon the definition of the workflow and simplifying structural and petrophysical assumptions, synthetic geological models for the traps from that WP1 database were built in Petrel™ to estimate the volumetric hydrogen storage resources. The approach used basic information on the traps which may not be readily available for all of them in WP1 database. All the structures are approximated by anticlinals with ellipse bases corresponding to the estimated area of the traps. The petrophysical properties such as porosity would be assigned based upon information available in the WP1 database complemented by assumed values when not available.

To compute the volumetric capacity, a storage efficiency factor is derived in a similar manner to CO_2 storage (Heidug, 2013) and considering the physical properties of hydrogen such as viscosity and density. This storage efficiency factor describes the macroscopic efficiency of hydrogen injection such as gravity segregation, capillary trapping (hysteresis effects). The volumetric capacities have not the same uncertainty level when considering for example a trap in a saline formation or unit or an underground gas storage. For underground gas storages, the volumetric capacities are based upon the working gas volumes as provided by GIE gas storage database. For oil and gas fields, the volumetric capacities are based upon the oil and gas recovery factor when available or their worldwide average. The Storage Resources Management System (SPE, 2018) is used to rank the different storage resources.

The approach was validated considering published hydrogen capacity for two aquifer structures (Luboń & Tarkowski, 2020 & 2021) in Poland by Hystories partner as illustrated below where the agreement is very good between published and estimated capacity:

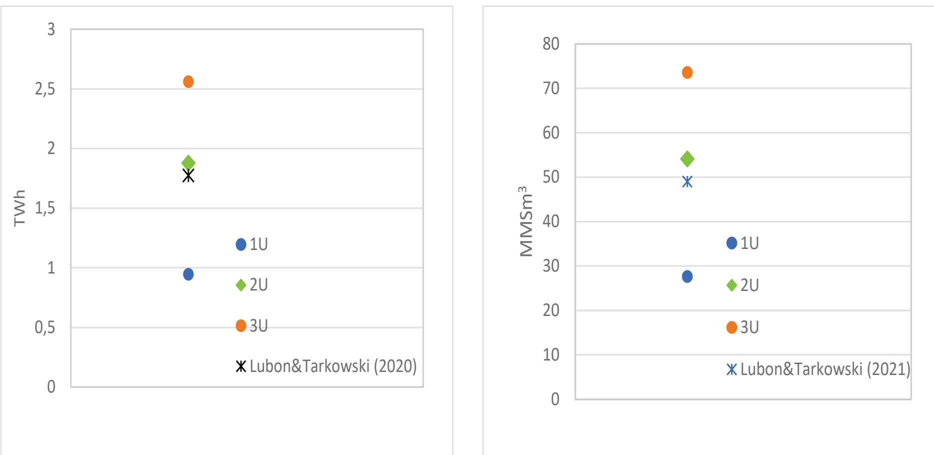


Figure 3: Comparison of published capacity estimate and Hystories estimation with its uncertainty range (1U-3U)

Country results are provided for all European countries and illustrated below for Belgium and Austria. The different storages (underground gas storage; depleted oil & gas fields, saline aquifers) are classified based upon the SPE Storage Resource Management System in terms of capacity, contingent and prospective storage resources respectively.

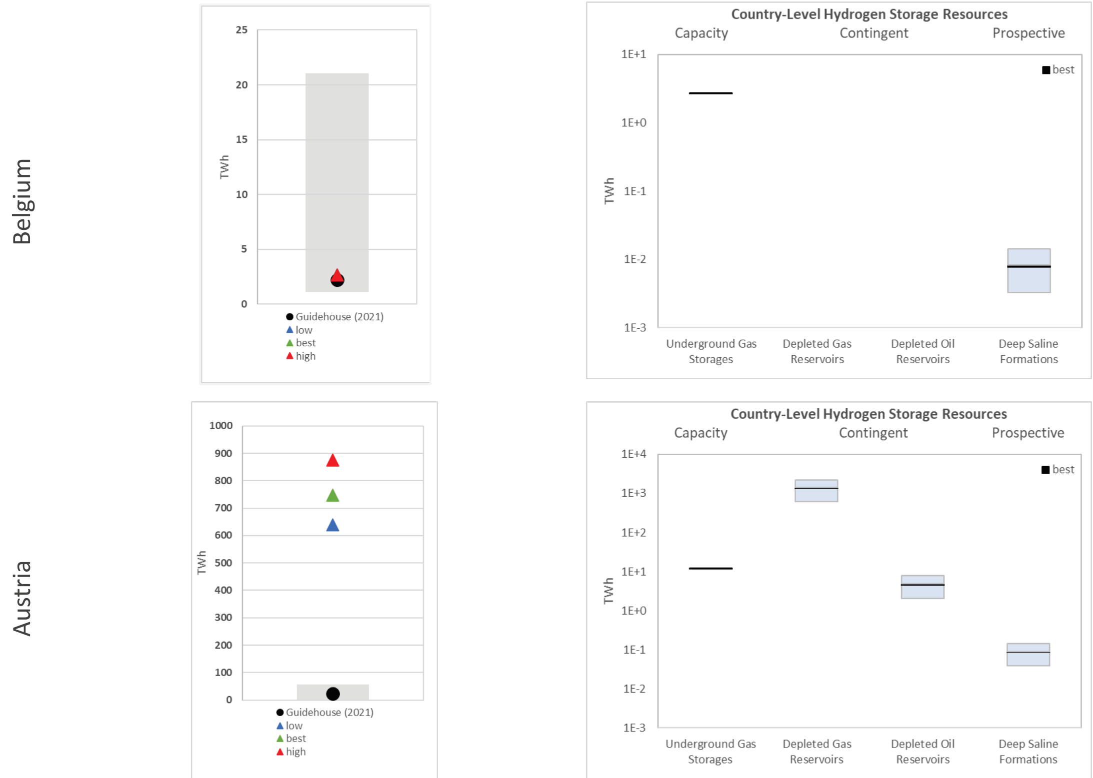


Figure 4: Comparison of published capacity estimate (left, from Guidehouse report, based on current natural gas storage capacity) and storage requirements (grey bar) from Hystories, and Hystories capacity estimates (right) with their uncertainty estimates (blue bars)

The capacity of the onshore and offshore traps is displayed on a geographical map on Figure 5 below, and per country and porous storage type on Figure 6:

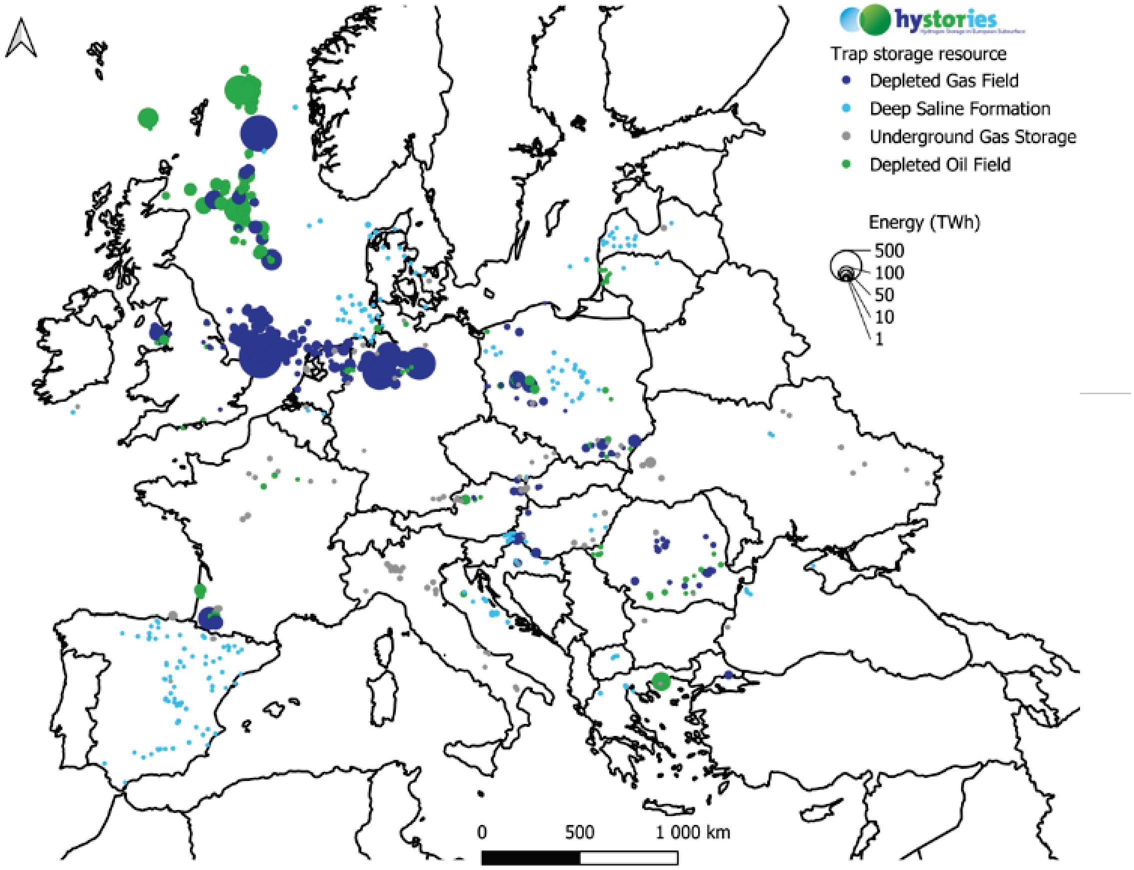


Figure 5: Hydrogen resource estimate for traps in Europe

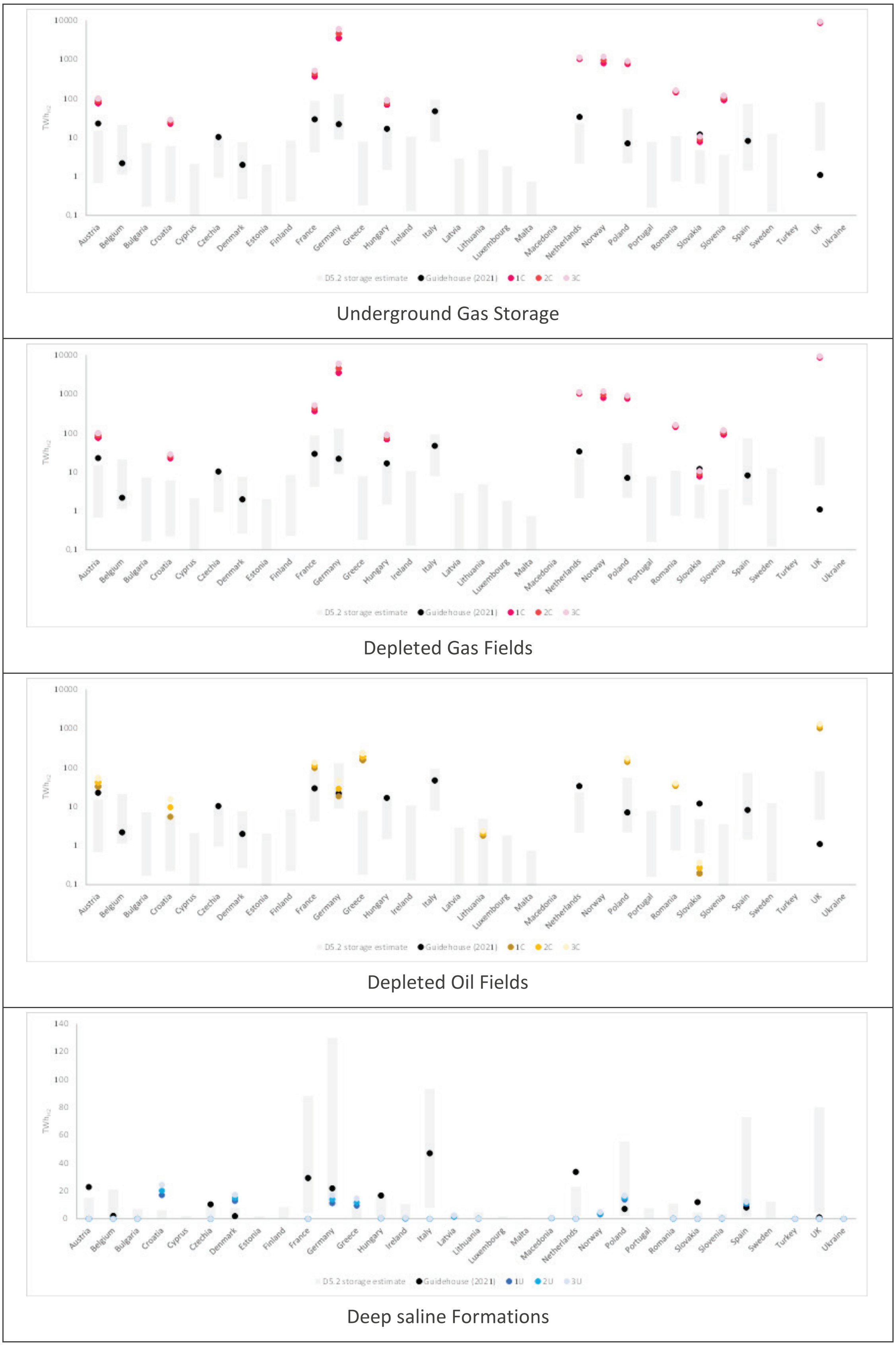


Figure 6: Hydrogen resource estimates for different storage in Europe. Bars represent the estimated uncertainty ranges from D5.2

The modelling work on realistic industrial scale multiphase flow 3D models with SLB- Eclipse™ was initiated on one commercial natural gas storage case to investigate gravity segregation, viscous fingering, mixing and containment. The model assumes seasonal hydrogen storage through new wells as the current well completion might not be well suited for hydrogen injection. The objective of this work is to evaluate the difference in storage capacity and deliverability for hydrogen between the industrial and simplified models established from public data as described above.

The first objective was to validate the modelling approach for capacity assessment and storage overall behaviour with a synthetic approach with respect to confidential site models provided by Advisory board member (D2.1), and with an aquifer model provided by MEERI-PAS. The latter could be published in D2.2.

Next, the approach using the simplified fluid model (black-oil with solvent option) was validated with respect to the compositional model along with investigations of key features such as the impact of gravity segregation, hydrogen contamination, mixing with the cushion gas, diffusion and hysteresis during the storage cycles. These modelling validations were performed on one of synthetic cases of the more than 800 traps to avoid confidentiality issues. Finally, to estimate the working gas capacity, a set of 21 traps including underground gas storages, depleted gas fields and deep saline formations, were selected near-by the proposed Hydrogen Backbone (GuideHouse, 2022). The average distribution of Working Gas to Total Gas is displayed in the table below:

Table 1: Average distribution of Working Gas to Total Gas

	WG/TV
underground gas storages	0.47
depleted gas fields	0.39
deep saline formations	0.50

2.2.2. Mineral geochemical interactions in abiotic conditions

The goal of this task was to assess the impact of abiotic reactions that might take place during hydrogen storage. In some cases, significant changes were reported but not specifically addressing the abiotic reaction (without bacterial activity). The abiotic reactions are firstly limited by the hydrogen dissolution in the brine of the storage. However, as hydrogen is an electron donor, it can be oxidized by various electron acceptors such as carbonates and bicarbonates, sulphates and other sulphur species, nitrate and other oxidized forms of nitrogen, ferric iron or oxygen. Consequently, several abiotic reactions are thermodynamically possible, but they are kinetically constrained.

A synthetic case was modelled with PHREEQC to illustrate the mineral reactivity with hydrogen using different modelling approaches for the kinetic reactivity by comparison to thermodynamic approach. The former shows much limited reactivity over the storage lifetime.

A synthetic carbonate model from Task 2.1 was used to confirm the lack of abiotic reactivity with CMG-GEM™ at the reservoir scale during seasonal storage (5 cycles).

The data provided by the Advisory Board members could be used to model the abiotic interactions between hydrogen and the rock minerals for six sites (D2.3). The simulations were performed with PHREEQC with the mineral and water compositions of the underground storage sites. For all the tested sites, sandstone storages, the mineral assemblage shows no changes under abiotic conditions during the storage lifetime. None of the minerals initially present are simulated to dissolve, including calcite and pyrite, and neither pyrrhotite precipitates when present.

2.3. Work Package 3 – Microbiology

The work package 3 has intensively focused on:

- Task 3.1: Enrichment and identification of microbial populations present in formation water samples with different physico-chemical properties from various reservoir types
- Task 3.2: Identification of changes in gas composition and examination of possible processes and microbial groups involved in hydrogen consumption at high and at slight overpressure
- Task 3.3: Modelling of the microbial reactivity of the storage site at full scale
- Task 3.4: Risk assessment and examination of the effects of environmental parameters such as pH, temperature and salinity on hydrogen-consuming microorganisms
- Task 3.4: Mitigation of the impact of microorganisms on hydrogen storage by developing inhibition strategies, such as through the application of biocides

Task 3.1 Microbiological Characterisation of formation water samples

Fifteen (15) formation water samples from nine (9) individual reservoirs of gas storage operators, members of Hystories' advisory board, have been analysed. Due to duplicate samples, some samples were pooled for the microbiological investigations, so that 11 formation water samples could be used for the further analyses. A planned sample could not be delivered by the operator to the lab due to technical reasons, and another one had to be sampled downhole a second time due to impurities present in the first batch. Nevertheless, more downhole samples (105 %) were analysed for the presence of microorganisms than originally planned (D3.1).

Conditions of the different formation water samples received in 2021 and 2022 are listed in the following table:

Table 2: Formation water samples used for microbiological characterization in Hystories Project.

Storage site	Formation water sample	Storage type	Pressure (bar)	Salinity (equivalent to % NaCl (w/v))	Temperature (°C)	pH
1	1	Depl. field	30 - 160	1.5	49	6.8
2	2	Depl. field	70 - 198	4.8	60	7.4
	3	Depl. field	70 - 198	1.7	60	5.8
3	4	Aquifer	100	0.1	66	6.2
4	5	Aquifer	100 - 200	1.4	91	10.2
5	6	Aquifer	45 -70	0.1	34	7.5
6	7	Depl. field	35 - 161	3.6	41	6.5
	8	Depl. field	35 - 161	3.7	41	6.5
	9	Depl. field	35 -161	5.2	48	6.4
	10	Depl. field	35 - 161	6	48	7.0
	11	Depl. field	35 - 161	3.6	48	6.8
7	12	Aquifer	90 - 130	10	64	5.9
	13	Aquifer	90 - 130	0.6	64	6.0
8	14	Depl. field	34 - 78	2.8	40	6.5
9	15	Aquifer	100 - 200	16.3	88.3	5.7

Based on molecular biology analyses, microorganisms were detected in all investigated deposits, except in one deposit with a salinity of 1.4 % NaCl and a temperature of 91 °C. By qPCR methods, the copy numbers of their specific target genes were quantified. The diagram below shows some results of molecular-biological analyses targeting the major 4 groups of hydrogen-consuming microorganisms.

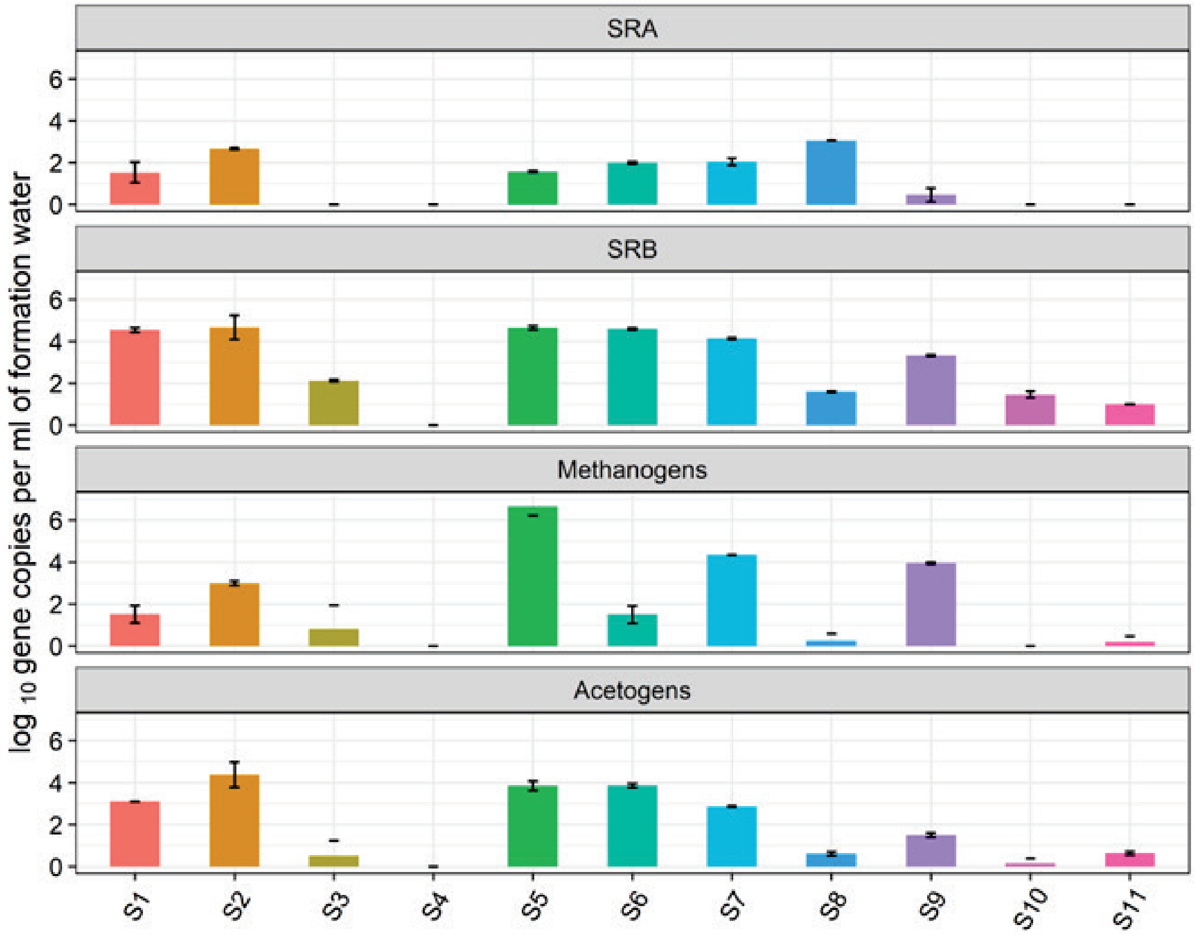


Figure 7: Molecular-biological analysis of hydrogen-related gene markers and microbial groups.

The results show that the proportion of major hydrogen consuming microorganisms varies significantly between different formation water samples. In 7 formation water samples all 4 major hydrogen-related gene markers were detected. Three samples contain low cell numbers, but at least one hydrogen-consuming microbial group is almost always present. The results of the molecular-biological analyses reveal the risk, potentially caused by hydrogen-utilizing microorganisms.

Through a combination of different microbiological methods (microscopy, molecular biology analysis and selective enrichment cultures), it was possible to make very robust statements about the microbial community in the samples. For this purpose, different selective growth media were used under strictly anaerobic conditions. The salinity and temperature were adapted to the conditions in the original structures. Depending on salinity and initial cell count in the samples, cultivation required up to 12 weeks. It was found that viable and active microorganisms of different groups were present in most of the formation water samples from different origins. Both the total number of cells and the complexity of the microbial populations in some samples were remarkable. High cell densities and activities were detected in samples with a salinity below 3 % NaCl (w/v) and temperature lower than 70 °C (samples 1, 3, 4, 6, 7, and 10). While storages with salinity higher than 3 % NaCl (samples 2, 8, 10) or with temperature higher than 80 °C (samples 5, 11) contained significantly lower cell counts and activities.

Beside hydrogen-oxidizing groups, the formation water samples were also analysed for various other physiological microorganism groups, e.g., hydrocarbon oxidizing or acid producing microorganisms. In the following table, only the enrichments of the hydrogen-oxidizing groups are listed A massive contamination with active hydrogen-consuming microorganisms such as methanogens, acetogens or sulphate-reducing prokaryotes was detected in 6 of the 11 reservoirs investigated.

Table 3: Microbiological characterization of formation water samples from porous storages.

Formation water sample	Pressure (bar)	Salinity (equivalent to % NaCl (w/v))	Temperature (°C)	pH	Hydrogenotrophic microorganisms relative cell number / group of MO	
1	30 - 160	1.5	49	6.8	+++	Methanogens, Acetogens, SRB, TRB, IR
2	70 - 198	4.8	60	7.4	+/-	Methanogens, TRB
3	70 - 198	1.7	60	5.8	+++	Methanogens, Acetogens, SRB, TRB, IR
4	100	0.1	66	6.2	+++	Methanogens, Acetogens, SRB, TRB
5	100 - 200	1.4	91	10.2	+	IR
6	45 -70	0.1	34	7.8	+++	Methanogens, Acetogens, SRB, TRB
7	35 -161	6.0	48	6.45	++	Methanogens, TRP, IR
8	90 - 130	10.0	64	5.9	+/-	Acetogens
9	90 - 130	0.6	64	6.0	+/-	Acetogens, SRB
10	34 - 78	2.8	40	6.5	+++	Methanogens, TRB
11	100 - 200	16.3	88.3	5.7	-	negative

Microbial risks associated with hydrogen-consuming microorganisms for these 6 storage sites should therefore be considered with particular caution. Another 4 samples contained microorganisms with lower cell numbers or activities.

By quantitative polymerase chain reaction (qPCR), the main group of hydrogenotrophic microorganisms, including sulphate-reducing archaea (SRA), sulphate-reducing bacteria (SRB), methanogens and acetogens, were determined in all formation water samples (see table below):

Table 4: Quantitative analyses of hydrogen-related microbial groups in the original formation water samples.

Formation water sample	Archaea	Eubacteria	Acetogens	Methanogens	SRA	SRB
1	1,7E+07	1,0E+06	7,8E+03	6,2E+06	3,8E+01	4,5E+04
3	7,1E+05	5,9E+05	7,5E+03	3,9E+01	9,9E+01	3,9E+04
4	6,2E+04	1,2E+05	1,3E+03	4,0E+01	4,6E+01	3,6E+04
6	4,2E+04	1,1E+05	3,6E+04	9,7E+02	4,6E+02	6,8E+04
7	1,8E+03	3,4E+02	3,2E+01	8,9E+03	3,3E+00	2,1E+03
8	5,3E+01	3,1E+00	1,3E+00	0,0E+00	0,0E+00	3,0E+01
9	1,1E+02	1,5E+01	5,3E+00	2,0E+01	2,5E-01	1,3E+02
10	3,8E+04	6,2E+03	7,4E+02	2,2E+04	1,1E+02	1,4E+04
11	2,2E+00	6,7E+00	4,4E+00	1,2E+00	1,0E-01	1,0E+01

The result of abundance analysis of the examined microbial groups is shown in the following figure:

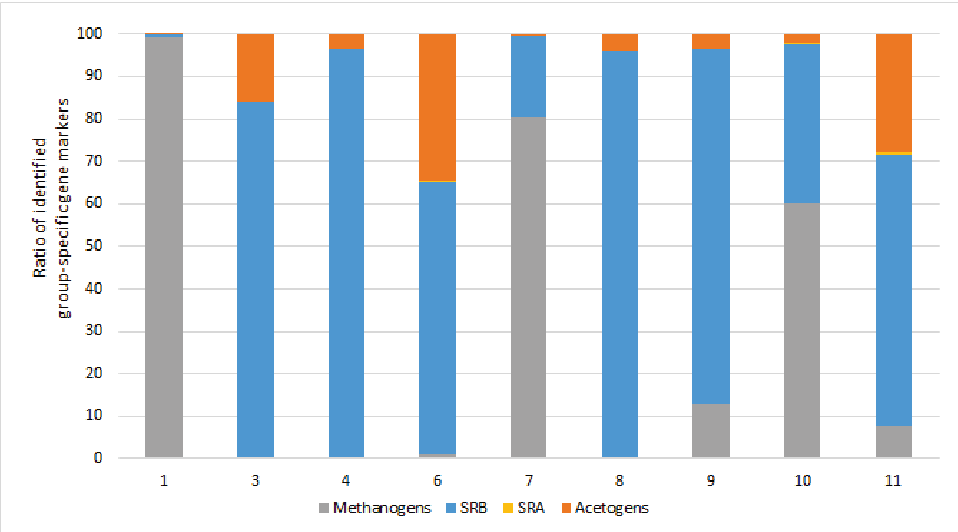


Figure 8: Abundance analysis of hydrogen-related microbial groups in the original formation water samples.

Task 3.2 Hydrogen consumption experiments at slightly increased and high pressure

To estimate the possible effects of microbial hydrogen consumption, simulation experiments were carried out under slightly increased pressure up to 3 bar and real storage pressure in autoclave units up to 100 bar. The experiments were carried out with those cultures from the original downhole samples of the reservoirs that had achieved sufficiently high cell numbers or activity in the previous enrichment cultures. Accordingly, seven series of experiments listed in the table below were carried out.

Table 5: Formation water samples and microorganisms used to test potential stimulation of microbial hydrogen consuming processes.

Sample	Salinity of formation water (% NaCl)	Incubation temperature (°C)	pH of formation water	Pressure at high-pressure tests	Hydrogen-consuming microbial groups*
1	1.5	50	6.8	30 bar	SRP, methanogens, acetogens
2	1.7	60	5.8	70 bar	SRP, acetogens
3	0.1	60	6.2	100 bar	SRP, acetogens
4	0.1	30	7.5	45 bar	SRP, methanogens, acetogens
5**	1.5	50	6.8	30 bar	SRP, methanogens, acetogens
6	2.8	40	6.5	35 bar	SRP, methanogens
7	4.9	45	6.7	35 bar	TRP

* SRP=Sulphate reducing prokaryotes; TRP=Thiosulfate reducing prokaryotes

** Sample #5 is a repeated test of storage sample #1

First, the different microbial groups were cultured separately in specific growth media until they reached the minimum cell content required for subcultures. Mixtures of these enrichment cultures were then adapted to original formation water with 100 % hydrogen in the gas phase and in combination with core material for 1-2 weeks before being used as inoculum for the experiments.

Low pressure tests

Hydrogen consumption tests at slightly increased pressure were performed in 125 mL glass bottles containing a total of 60 mL of formation water and a mixed enrichment culture. Core cuttings and/or an artificial carbon source ($NaHCO_3$ or $CaCO_3$) were added to stimulate microbial growth. Pure hydrogen gas was injected to an initial absolute pressure of 1,500 - 2,000 mbar. For control purposes, abiotic batches without the addition of microorganisms were also prepared in the same way.

Various hydrogen consumption tests were carried out to study the influence of parameters, such as type of carbonate, salinity, sulphate content or pH value.

During the experimental phase of 50 days, the absolute pressure was monitored regularly. When the pressure dropped below atmospheric pressure, either H_2 or N_2 gas was added. Any changes in gas composition (H_2, CH_4, CO_2) in the gas phase were determined by gas chromatography. Liquid samples were taken at regular intervals for cell count, pH measurement and chemical analysis. In addition, liquid samples were taken at the beginning and end of the hydrogen consumption test to quantify specific groups of hydrogen-consuming microorganisms by qPCR.

In all seven case studies, microbial activities were detected at low overpressure, although there are significant differences between the samples investigated. This concerns both the hydrogen turnover rate and the groups of microorganisms involved. While methanogenic microorganisms dominated in some of the tests, acetogenic or sulphate-reducing microorganisms developed in other simulation tests depending on the composition of the inoculum and the respective experimental conditions (e.g., pH value, availability of sulphate). In our experiments we determined maximum turnover rates of up to 500 mM for the enriched cultures of sulphate-reducing microorganisms and up to 27 mM for methanogens.

As an example, the following figure shows hydrogen consumption and corresponding methane formation with core material and carbonate addition respectively.

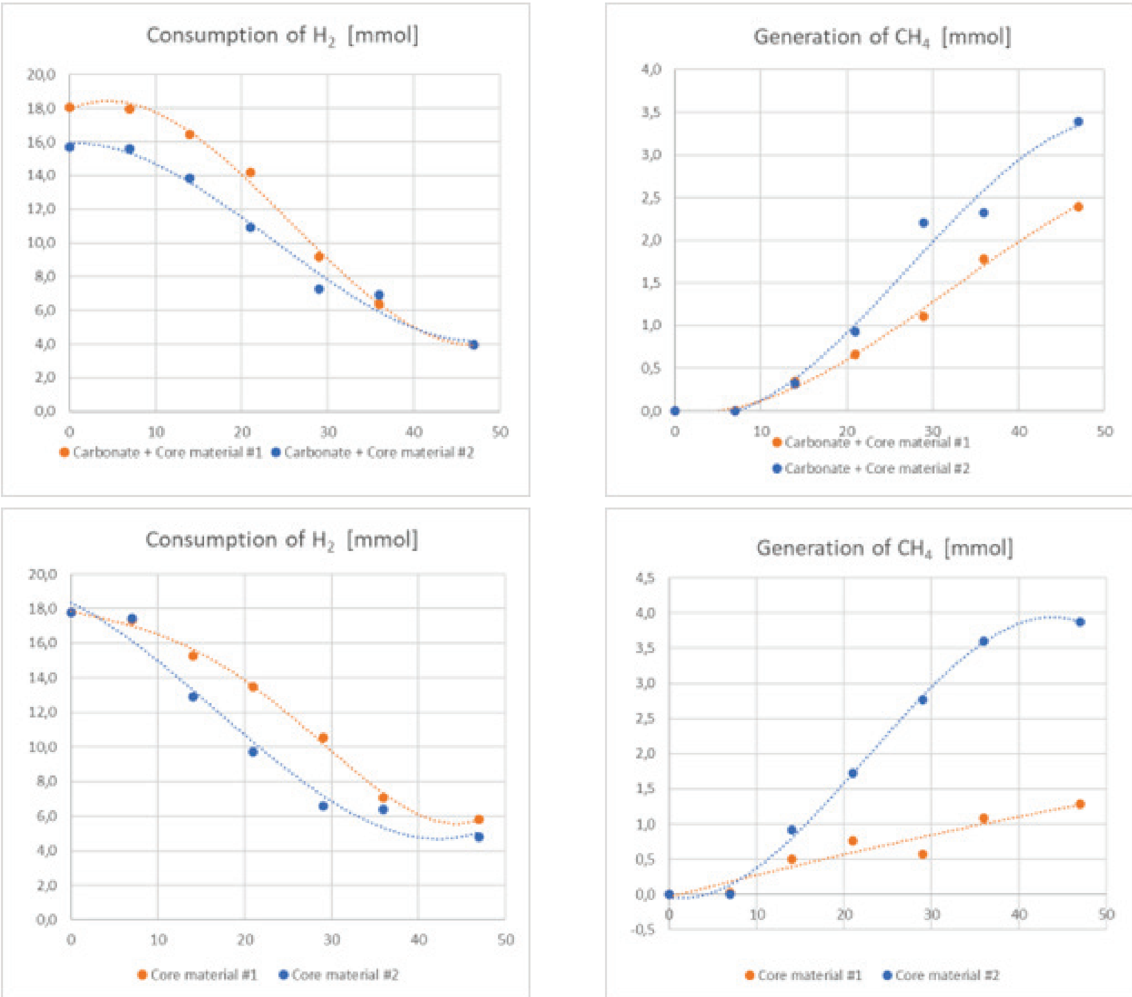


Figure 9: Hydrogen consumption and methane formation with different carbon sources at low pressure.

During the 47-day incubation period, 11.8 - 14.1 mmol of hydrogen were consumed and 1.3 - 3.9 mmol of methane were produced with a resulting hydrogen consumption rate between 4.6 and 5.7 mmol/m³/day and the methane production rate between 0.8 and 2.1 mmol/m³/day. With a consumption of ~12 mmol hydrogen and a formation of ~3 mmol methane the conversion corresponds to the theoretical H_2:CH4 ratio (4:1). In the tests with core material, this is valid for one set of tests, while the second set shows a significantly lower rate.

Through the experiments it became clear that the microorganisms can use both the carbonate contained in the core material of the reservoir and artificially supplied carbonate as a carbon source to produce methane or acetate. Moreover, the microbial conversion rate of hydrogen is higher with carbonate than with real core material likely because of a better solubility.

High pressure simulation tests

The hydrogen consumption tests at high pressure were carried out in high-pressure reactor units prepared with formation water, a mixed enrichment culture and core material (if available). The high-pressure reactors were first purged seven times with hydrogen for the experiments and then set to the corresponding target pressure of the reservoir before the start of the simulation experiment. A maximum rate of pressure change of 4 bar/min was maintained for the filling in order not to damage the bacterial cells. All high-pressure experiments were carried out for reservoirs with a minimum hydrogen conversion rate recorded in previous lab experiments. The composition of the gaseous phase, the pH and microbial composition in the liquid phase were determined at least twice, at the beginning and at the end of the high-pressure test. Various methods were used for analytical support of the simulation experiments, including microscopy, gas chromatography, ion chromatography, microbiology and molecular biology.

Analogous to the example of the low-pressure test, the following figure shows the result of the high-pressure test for the same sample.

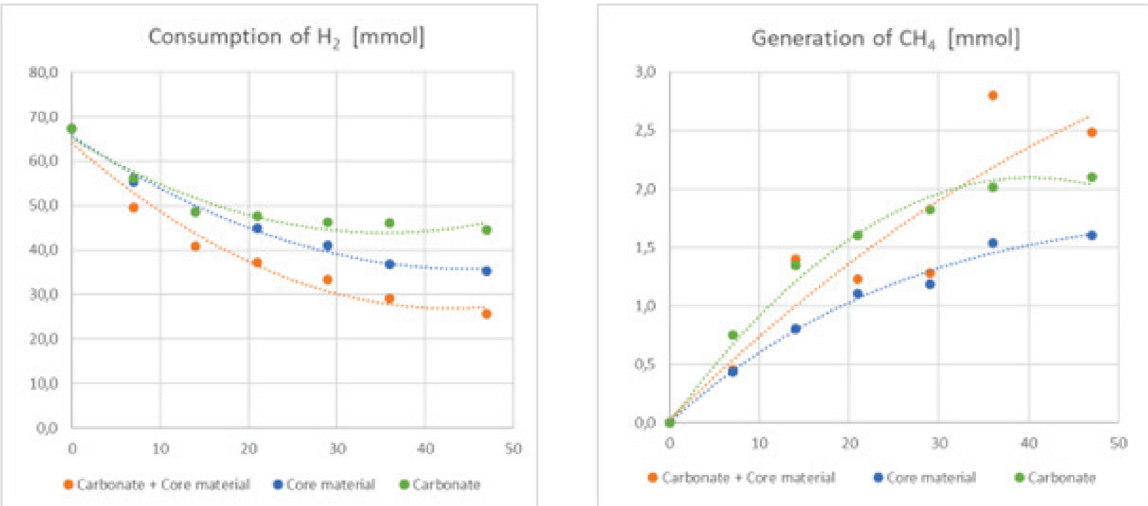


Figure 10: Hydrogen consumption and methane production with different carbon sources at high pressure.

Hydrogen was consumed and methane was generated simultaneously in all three experimental variants. The maximum hydrogen consumption and methane production rates were observed in the first 14 days of the experiment and amounted to a maximum of 9 mol/m³ culture and day. The highest methane production rate was 0.5 mol/m³/day and was observed for reactor 1 with carbonate and core material as carbon sources.

Not all high-pressure tests yielded conclusive results, which may be due to the relatively large gas volumes simulating the real storage pressure. As a result, small conversion rates can no longer be detected by gas chromatography. In some of these experiments, a very significant increase in pH was observed, which apparently rose to pH 9.5 due to microbial activities, so that further microbial processes are inhibited as a result. The extent to which this effect occurs under real conditions in a porous reservoir must be clarified by further investigations.

In summary, it can be concluded that through the simulation tests with enriched reservoir samples and under practical conditions, it has been shown that microbial hydrogen depletion is highly likely to occur in some reservoirs and that there is thus a real risk for certain reservoir configurations. A precise prediction about the extent and direction of these processes cannot be made in general, as this depends on numerous factors. Case-specific investigations are required for a corresponding risk analysis.

Task 3.3. Modelling of the microbial reactivity of the storage site at full scale

A microbial reactivity model was established using PHREEQC to simulate the methanogenesis and sulphate-reduction reactions observed in the laboratory tests. These laboratory tests and modelling were carried out at a specific salinity: 16 300 mg/L. Bacteria development and reactivity are highly dependent on salinity. Therefore, the model and kinetics presented below are valid only for this range of salinity. The experiments were carried out at low and high pressure. The methanogenesis and sulphate-reduction reactions were modelled by double Monod-type kinetic rates which combined the consumption of bicarbonate and sulphate ions and growth of microorganisms as follows:

HCO_3^- utilization rate:

$$\frac{d\, HCO_3^-}{d\, t} = K_{max}\, [X_{mt}] \left(\frac{[HCO_3^-]}{Ks_{\, HCO_3^-} + [HCO_3^-]} \right) \left(\frac{[H_2]}{Ks_{H_2} + [H_2]} \right)$$

Methanogenic cell growth rate:

$$\frac{d\, X_{mt}}{d\, t} = -Y_{mt} \frac{d\, HCO_3^-}{d\, t} - D_{mt}[X_{mt}]$$

Where X_{mt} is the biomass, Kmax is the maximum substrate utilization rate, and $Ks_{\, HCO_3^-}$ and Ks_{H_2} are the half-saturation constants, Y_{mt} is the yield rate and D_{mt} is the methanogenesis biomass decay coefficient.

The same equations can be used to express sulphate reduction (sr) reactions:

$$\frac{d\,SO_4^{2-}}{d\,t} = K_{max}\,[X_{sr}]\,\left(\frac{[SO_4^{2-}]}{Ks_{SO_4^{2-}} + SO_4^{2-}}\right)\left(\frac{[H_2]}{Ks_{H_2} + [H_2]}\right)$$

$$\frac{d\,Xsr}{d\,t} = -Y_{sr}\,\frac{d\,SO_4^{2-}}{d\,t} - D_{sr}[X_{sr}]$$

The values of Kmax and Ks can be estimated from the laboratory tests results and then adjusted with PHREEQC to match the laboratory observations regarding the different substrate consumption rates as detailed in D3.3.

To simulate a microbial kinetics on the sulphate-reduction and methanogenesis terminal electron accepting reactions in solution it is necessary to use an uncoupled thermodynamic database. In this database, the species that can present various redox states are duplicated to oxidized and reduced species. Dealing now with different species, PHREEQC can consider a reaction between these species and include a kinetic control. The thermodynamic database established in WP2 was used for these calculations (D2.4).

The core used in the tests contains carbonate minerals namely dolomite and calcite. These minerals are expected to react with the formation water in precipitation/dissolution reactions, eventually providing a source of carbon to microorganisms and maintaining the methanogenesis reaction over time. The mineral and brine compositions were measured in the experiments. The geochemical reactions involving calcite, dolomite and pyrite were kinetically modelled. Both abiotic and biotic test were modelled

The abiotic high-pressure test showed no hydrogen consumption, nor methane generation. The model also predicts the absence of hydrogen reactivity, and no CH_4 nor H_2S generation. The XRD analyses showed some precipitation of calcite and dolomite. This precipitation is also predicted by the model.

In biotic high-pressure test, the formation water is enriched in methanogenic bacteria in contact with the core and H_2 gas phase in the reactor. The evolution of the gas phase predicted by the model is displayed in the figure below, together with the values measured in the laboratory during the tests.

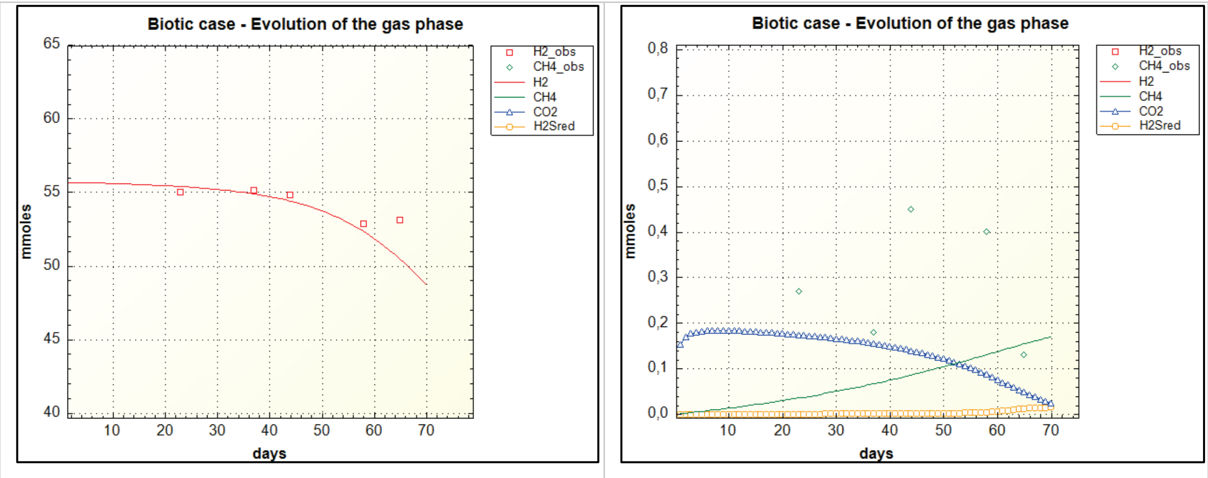


Figure 11: Evolution of the gas phase between model and experiment for the biotic test at high pressure

Laboratory trend over 70 days at high pressure were well reproduced by the 0D model. Especially, at laboratory scale, the model predicts a consumption of 5 % of hydrogen at the end of the experiment. A production of methane and H_2S (up to 5300 ppm) in the gas phase was also modelled. This concentration is overestimated.

Regarding the ions in water, a quick decrease of calcium, magnesium and carbonates is predicted at the beginning of the experiment because of precipitation reactions (calcite and dolomite precipitation) and carbon outgassing as CO_2 as shown in the figure below.

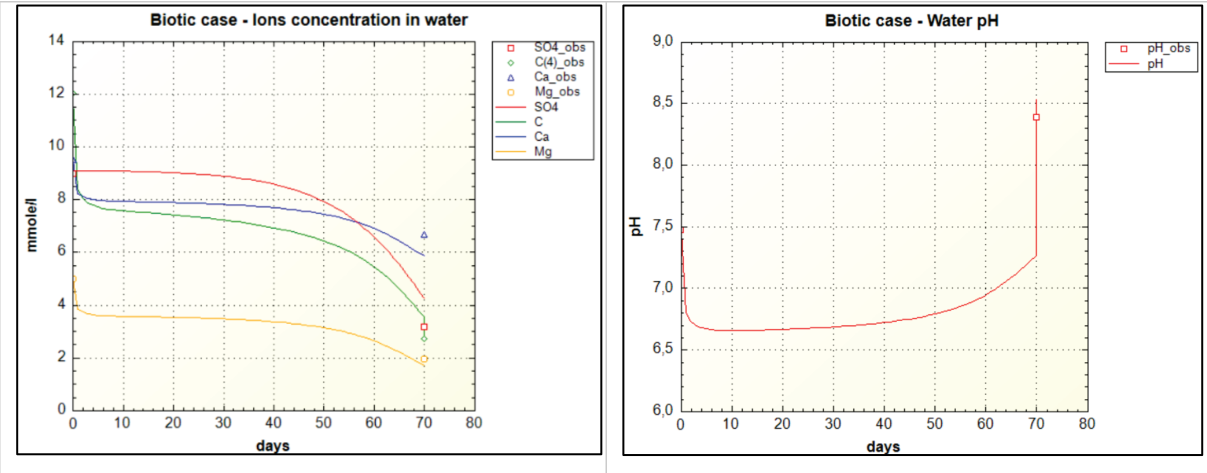


Figure 12: Evolution of the water phase and pH between model and experiment for the biotic test at high pressure

Once all the carbonates in water have been depleted, precipitation stops, and dolomite starts to dissolve, providing more carbonates to bacteria. Sulphate is not involved in precipitation reactions, but it is reduced quickly by bacteria. These last reactions are significantly slowed down when pH becomes higher than 8.

Regarding bacteria, the model predicts an increase of active methanogenic and sulphate reducing bacteria which are then compared to the total number of cells of the sample as measured at the beginning and end of the experiment as shown below:

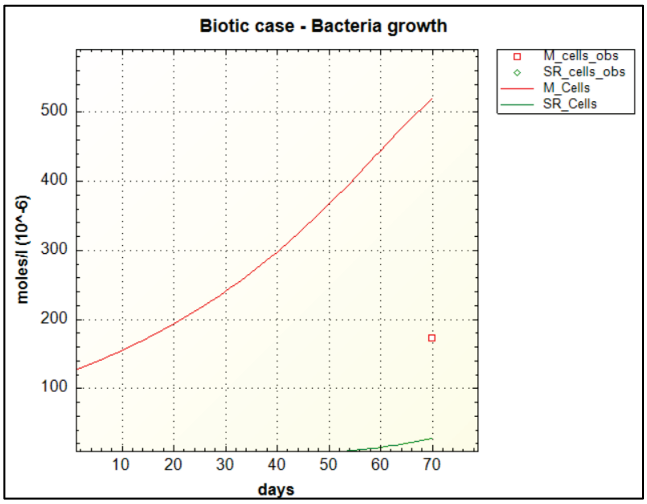


Figure 13: Evolution of the active bacteria between model and experiment for the biotic test at high pressure

This total number of cells includes both methanogenic and sulphate reducing bacteria. However, as the water sample was enriched only in methanogenic bacteria, it can be assumed that most of these measured cells would be methanogenic.

The simulation of the laboratory tests allowed the determination of kinetic parameters to match the microbial catalysis of methanogenesis and sulphate-reduction reactions under H_2-rich conditions, at reactor scale. These kinetic parameters can now be used to estimate the microbial risk of H_2 consumption at reservoir scale.

It needs to be reminded that the kinetics measured in the laboratory represent the optimal conditions for bacteria growth and H_2 consumption, while at reservoir scale, the kinetics can be orders of magnitude lower because of the less favourable conditions and the multitude of bio-geo-chemical reactions that can take place.

A commercial 3-D 3-phases compositional model designed for the advanced modelling of recovery processes involving the injection of steam, solvents, air and chemicals, STARS™, was used to model the experiment at the storage scale. The modelling concept to bacterial reactivities assumes the reaction should occur at the interface between hydrogen and brine based upon qualitative laboratory experiences. Consequently, to enable localized reactions, bacteria concentration is defined spatially within the model.

STARS™ cannot directly handle Monod-type reactions, it is not possible to model the methanogenesis reaction as defined in PHREEQC. Thus, the methanogenesis reaction is combined with the dissociation of CO_2 in the water phase and the STARS™ parameters are adjusted to best match PHREEQC reaction rates, Kmax and Ks as detailed in D3.3. Similarly for sulphate reduction reaction combined with the hydrosulphide reaction as detailed in D3.3.

The synthetic geological model presented and used in D2.3 is taken as the application case. The model is assumed as a saline aquifer formation (initial gas saturation = 0 %). The model does not assume any brine recharge i.e. the model boundaries are closed: no brine influx from the surroundings. The initial pressure is assumed to be 130 bar, the temperature is constant at 50 °C and the water composition is slightly modified compared to the one used in PHREEQC, as the sulphate concentration was fixed close to zero (5 mg/l) to simplify the model. **Sulphate reduction reactivity is thus underestimated on this first model and H_2S emission could be higher in real cases**.

The model aims to compute the evolution of the pressure and fluid composition within the storage assuming seasonal cycling (after 10 months of initial fill-up) and injection/withdrawal through 4 horizontal wells at a rate of 0.1 $MMSm^3$/d/well with a withdrawal rate equal to the injection rate.

Two simulations were performed either using the same kinetic parameters as PHREEQC or based upon a volumetric upscaling similar to the upscaling of chemical reactivity for water flooding upscaling. This implies a significant damping of the reactivity. No significant difference was forecasted by the model in terms of total mass of hydrogen in the storage No significant change in mineralogy is forecasted both for cases with upscaled reactivity and with laboratory derived reactivity.

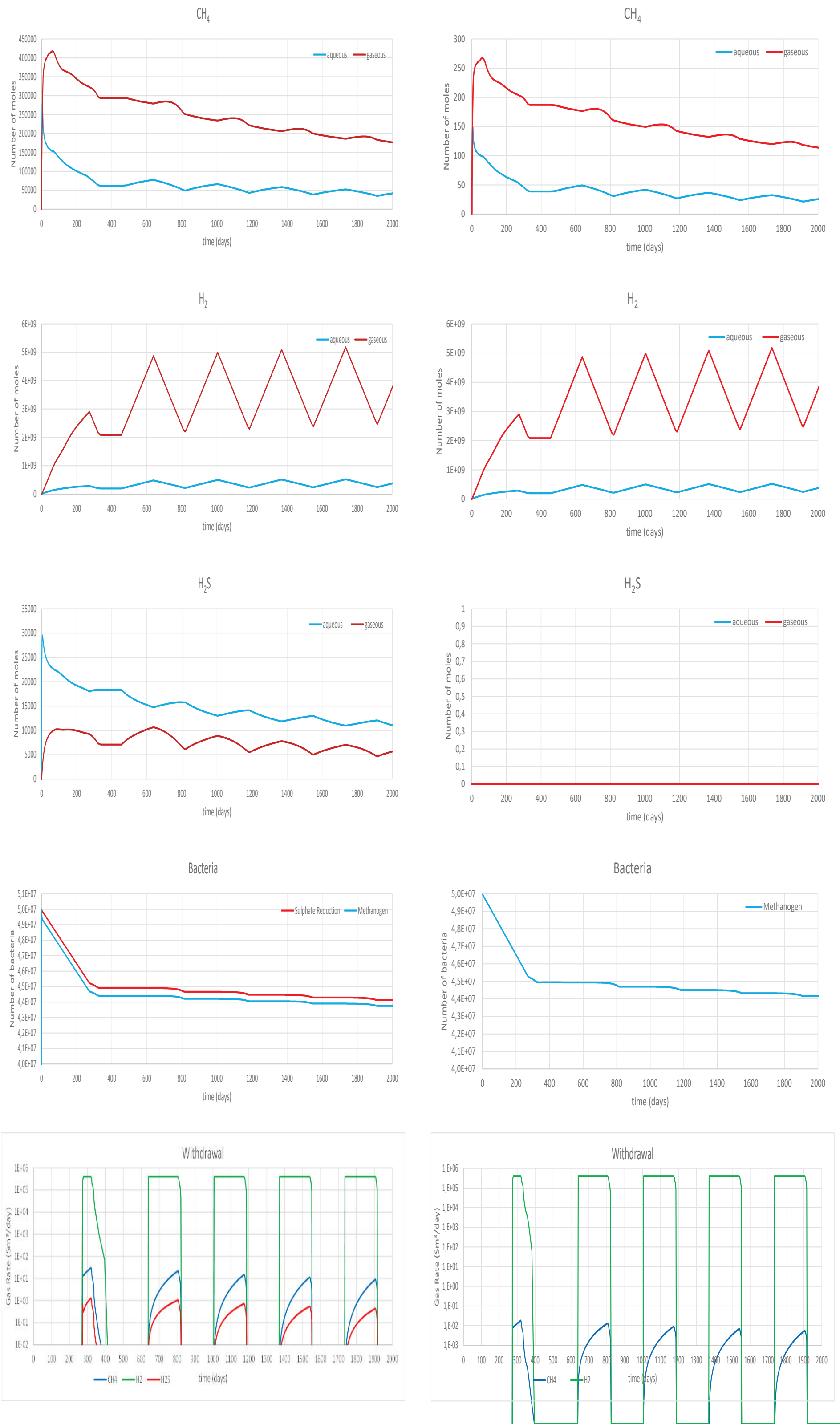


Figure 14: Evolution of the number of moles for methane, hydrogen, hydrogen sulphide and flow rates during withdrawal period for upscaled (right column) and laboratory-derived (left column) reaction parameters (scales are different)

According to the model, most of the reactivity occurs at the start of hydrogen injection as in the current approach the bacteria activity, either methanogen or sulphate reduction, are correlated to the aqueous concentration of CO_2 and SO_4 respectively. As implied by the model concept, most of the reactions take place at the interface between hydrogen-rich and hydrogen- poor zones. In the zone swept by hydrogen, the reactivity decreases due to reactant impoverishments (see D3.3 for corresponding illustrations). Depending on the selected scale (laboratory scale or upscaled reactivity), the 3D model indicates a maximum amount of impurities between 4.10^{-5} and 0.06 % for methane and 0 and 54 ppm for H_2S as limited by the initial assumption on sulphate concentration. However, extension to field case of this modelling approach would require further validation and investigations of the current innovative approach. Field scale observations of the reactivity occurring during hydrogen injection in porous reservoirs will be necessary to set some of the parameters of the reservoir reactive transport models and provide predictions with confidence.

Task 3.4 Microbiological Risk assessment and mitigation strategies

In this work package, the relevant living conditions for the development of microorganisms in the deep biosphere were considered. Parameters were identified that can significantly limit the growth of hydrogen-using microorganisms and are therefore relevant for risk assessment.

Microbiological Risk assessment

The risks posed by intensive microbial hydrogen consumption in a porous underground reservoir are manifold. In principle, any microbial activity is detrimental to the operation of a porous underground structure. In addition to the quantitative loss of hydrogen, the deterioration of gas quality due to the formation of hydrogen sulphide (H_2S) is an important criterion for the storage operator. Due to the formation of bio-based solids (FeS) and biofilms, there is a risk of permeability reduction and well bore plugging. The laboratory experiments show that chemical changes in the formation water are possible e.g., the pH value or the dissolution of minerals such as $CaCO_3$ or $CaSO_4$. The development of microorganisms leads to an increase in complex organic substances, which can trigger secondary degradation processes by other bacterial groups. Sulphate-reducing microorganisms play a special role in the risk assessment due to their resilience and adaptation to extreme conditions and the formation of hydrogen sulphide. Possible consequences include corrosion (MIC) and acidification by H_2S, CO_2 and organic acids.

In addition to hydrogen, hydrogenotrophic microorganisms require a carbon source such as acetate, lactate, methanol, CO_2 or HCO_3^-. Experiments have clearly shown that the carbon source has a significant influence on the hydrogen turnover rate. Numerous comparative studies with real core cuttings from reservoirs and artificial carbonate additives clearly show that artificial carbonate ($NaHCO_3$) leads to higher turnover rates due to its better bioavailability, but that carbonates from rock material can also be used as a carbon source.

The availability of sulphate in the formation water has a decisive influence on the activity of sulphate-reducing microorganisms. The aqueous dissolution of calcium sulphide-sulphur mineral phases such as gypsum ($CaSO_4[2H_2O]$) and anhydrite ($CaSO_4$) can provide sulphate for sulphate-reducing microorganisms. Sulphate reducers compete with methanogens for available substrates and can displace the latter depending on environmental conditions.

Underground gas reservoirs typically have a temperature range of 20 to 110 °C or higher, allowing the development of mesophilic to hyperthermophilic microorganisms. This study showed high microbial activity at temperatures between 30 and 70 °C. (Hystories, Deliverable 3.1) Another important factor is salinity. Increased salt concentrations commonly result in decreased microbial activity and even causes cell death. However, there are microorganisms that are very well adapted to high salinity and can grow even in saturated brine. It has been demonstrated that the maximum salt tolerance for methanogenesis is lower at higher temperature, indicating an interaction between salinity and temperature. The tests on the effect of pH between 6.0 and 10.0 on hydrogen consumption clearly showed the influence on microbial activity, with pH values above 7.0 causing a significant reduction in hydrogen consumption. In our study, microorganisms from reservoirs were enriched at a pressure between 100 and 200 bar (Hystories, Deliverable 3.1). It was found that the activity of microorganisms such as acetogens is slightly increased at a hydrogen pressure of 45 bar compared to a pressure of 1 bar (Hystories, Deliverable 3.2). High pressure is not expected to have a negative impact on the growth and activity of microorganisms. On the contrary, since microorganisms can only use gases such as hydrogen and carbon dioxide when they are dissolved in aqueous solution, increased pressure improves the solubility of the gases and thus their availability for microbial processes. In addition, pressure, in conjunction with temperature and pH, determines the dissolution of rock materials, which could, for example, increase the concentration of HCO_3^- from calcite.

As a result of this study, the parameters temperature and salinity of the storage systems were identified as essential environmental factors for the control of hydrogenotrophic microorganisms. It has been demonstrated that microorganisms enriched from the reservoir samples were still very active at a temperature of over 60 °C. In agreement with previous isolates from similar sites, it can be stated that microbial activity is still present in the temperature range between 55 °C and 70 °C. A salinity of above 1.7 M generally leads to an inhibition of numerous microorganisms. Above this salinity, the activity of hydrogenotrophic methanogens drops drastically. However, if both stress factors act simultaneously, the respective limits decrease considerably, so that microbial colonisation of reservoirs with temperatures above 55 °C and salinities above 1.7 M is very unlikely and these therefore appear to be well suited as hydrogen reservoirs.

As part of WP7.3, almost 500 traps, storages and hydrocarbon reservoirs were analysed in terms of the above-described critical limits for salinity and temperature. As shown in the figure below, 192 traps can be identified with a correspondingly low microbial risk. Accordingly, 136 structures have a high-risk potential and 164 a medium risk. On this basis, we can already make a very basic risk classification for potential storage sites at a very early planning stage. The structures with medium or high risk must be evaluated regarding further parameters to further limit the risk if necessary.

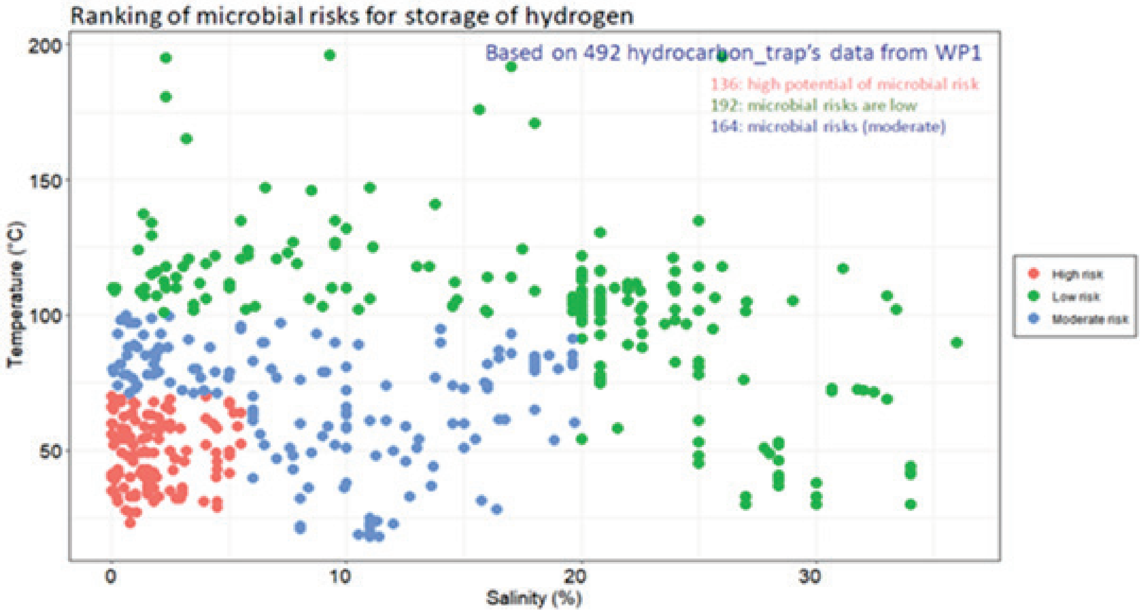


Figure 15: Ranking of microbial risks for storage of hydrogen (Source Hystories, D7.3)

Clearly, in addition to temperature and salinity, other factors such as carbonate availability, sulphate concentration, organic compounds, mineral composition (carbonate and sulphate source for microorganisms), pH and microbial community need to be included in the risk assessment. As a result of a classification of those parameters, a risk assessment diagram as an initial guide for classifying microbial risks (low risks, moderate risks and high risks) for underground gas storages is proposed. The diagram is structured in such a way that the four most important parameters (temperature, salinity, carbon and sulphate availability) are considered one after the other (from top to bottom) and ultimately results in a microbiological evaluation of the reservoir. A parameter becomes the primary control when it has reached the inhibition threshold for microbial life (low risks and moderate risks).

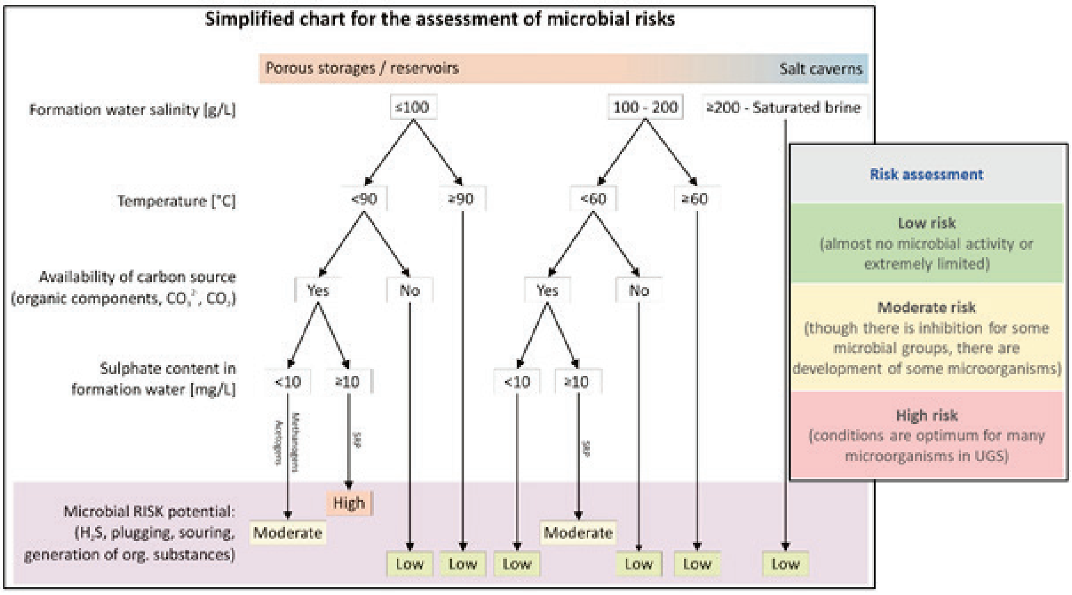


Figure 16: Simplified chart for a risk assessment for UGS based on temperature, salinity, carbon and sulphate availability. From D3.4

The ranking of microbial risks for the reservoirs investigated in the Hystories project based on available data and laboratory analyses is shown in the table below. Since no complete information was available on the rock composition of the investigated reservoirs, it was assumed as a worst-case scenario that carbon and sulphate sources are present in the rock.

Table 6: Ranking of microbial risks for storage sites investigated in Hystories project

Storage site	Formation water	Salinity (NaCl %)	Temperature (°C)	Risk ranking 1	pH	Hydrogen-consuming groups detected	Risk ranking 2
1	1	1.5	49	High	6.8	Yes* (SRB, methanogens, acetogens)	High
2	2	4.8	60	High	7.4	±	Moderate
	3	1.7	60	High	5.8	Yes* (SRB, acetogens)	Moderate
3	4	0.1	66	High	6.2	Yes* (SRB, acetogens)	High
4	5	1.4	91	Moderate	10.2	not detected	Low
5	6	0.1	34	High	7.5	Yes* (SRB, methanogens, acetogens)	High
6	7	3.6	41	High	6.5	±	Moderate
	8	3.7	41	High	6.5		Moderate
	9	5.2	48	High	6.4		Moderate
	10	6	48	High	7.0		Moderate
	11	3.6	48	High	6.8		Moderate
7	12	10	64	Moderate	5.9	±	Moderate
	13	0.6	64	High	6		Moderate
8	14	2.8	40	High	6.5	Yes* (SRB, methanogens)	High
9	15	16.3	88.3	Moderate	5.7	±	Moderate

± detected by molecular analysis but not by viable cultivation

*: hydrogen-consuming groups successfully enriched at the laboratory

If all parameters are included: Temperature, salinity, pH and microbial analysis of the formation water into the consideration, there are 4 samples with high microbial risk, 1 sample with low microbial risk and 10 samples with moderate microbial risk. The result of risk ranking 2 is also consistent with our stimulation tests, where microbial hydrogen consumption activity was measured under conditions close to real storage conditions.

Mitigation of microbial risks for under-ground hydrogen storages

The ability to control biological activity in geological structures, particularly in open systems such as porous reservoirs, is very limited. Biocides and other biologically active substances (e.g. nitrate) have been used successfully in oil reservoirs and gas storages. The treatment of local reservoir damage due to bioactivity (e.g. FeS precipitation) can be controlled by acidification or intensive biocide application, especially in spatially limited areas (near-borehole areas).

Based on the risks and growth parameters described above, strategies to modify the ecological conditions of a reservoir can be derived. For this purpose, pH values below 5.0 and above 10.0 are considered, whereby microorganisms are restricted in their metabolic activity and inhibited at extreme pH values. Increasing or decreasing the pH can therefore be considered as a possible treatment strategy, although the possible consequences (solubility of H_2S, CO_2, corrosion, etc.) must be considered beforehand. An interesting aspect could be the pH increase due to hydrogen consumption, which has been observed in some experiments. Increasing the pH to values above 9.0 in these experiments led to the inhibition of further microbial material conversions. These processes should be investigated in more detail in further experiments and could play an important role in the risk assessment of hydrogen storage.

A common method of controlling microbial activity in underground structures is the application of biocides. It is important to ensure that the concentration does not fall below the effective concentration, for example through dilution in an open porous system, as the biocide becomes ineffective and may even act as a nutrient for microorganisms. This dilution effect is inevitable in porous reservoirs at some distance from the injection well. Each biocidal substance has a minimum effective concentration that can be determined in the laboratory using test cultures. A distinction must be made between killing and inhibiting effects.

Three EU registered biocides were initially selected for the biocide tests to be carried out. In addition, an internal biocidal substance has been tested. Using the enriched cultures from WP3.1, various biocide tests were carried out to determine the effective concentrations for each culture. For this purpose, dilution series of the biocides were prepared and each dilution level, as well as a biocide-free control, was inoculated with a sample of the previously activated microbial culture. The biocide series were incubated for up to 12 weeks and analysed for growth or microbial activity (e.g. FeS), indicating an ineffective biocide concentration. With these biocide tests, the lowest effective concentration could be determined very precisely.

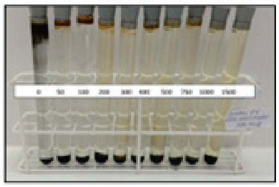
This following figure shows triplicate biocide tests with cultures of sulphate reducing microorganisms after a cultivation for 12 weeks with increasing biocide concentrations. At 0.1 % and 15 % salinity, the activity of all test cultures was completely inhibited by a biocide concentration of 50 ppm. In saturated brine, two biocides required concentrations of 200 ppm to inhibit microbial activity:

0.1% salinity

	Test concentration (ppm)										
Biocide:	0	50	100	200	300	400	500	750	1000	1500	2000	control
XC82681	+++	+-	-	-	-	-	-	-	-	-	-	-
XC82205	+++	-	-	-	-	-	-	-	-	-	-	-
Grotan OX	+++	-	-	-	-	-	-	-	-	-	-	-

15% salinity

	Test concentration (ppm)										
Biocide:	0	50	100	200	300	400	500	750	1000	1500	2000	control
XC82681	+	-	-	-	-	-	-	-	-	-	-	-
XC82205	+	-	-	-	-	-	-	-	-	-	-	-
Grotan OX	+	-	-	-	-	-	-	-	-	-	-	-



32% salinity

	Test concentration (ppm)														
Biocide	0	10	20	30	40	50	75	100	200	300	400	500	750	1000	1500	control
XC82681	++	+-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
XC82205	++	++	++	++	++	++	++	++	-	-	-	-	-	-	-	-
Grotan OX	++	++	++	++	++	++	++	++	-	-	-	-	-	-	-	-
In-house agent	++	++	-	-	-	-	-	-	-	-	-	-		-	-	-

Figure 17: Results of biocide tests with an active culture of sulphate reducing microorganisms

2.4. Work package 4 – Material and Corrosion

The final aim of WP4 of the Hystories project was to highlight the steel grades that would be the most adapted for hydrogen underground storage wells.

In the course of WP4, the tests for selected materials in D4.2 (list of steel grades to be investigated) were carried out in autoclave tests.

The three carbon steel grades K55, L80 and the welded J55 were tested in the full test program. Other selected materials were tested under certain conditions. The full test program includes: autoclave tests including: time to failure, hydrogen content, SEM investigation of surface layer and permeation tests. Ripple load tests were also performed for some steel specimens in order to determine the resistance of the steels in cyclic conditions.

Experiments are described in detail in report D4.1_Final protocol for material testing. In this report only results are described.

In Figure 18and Table 7 give an overview of diffusion coefficients derived from permeation measurements with hydrogen of the investigated steel grades is shown.

For the ferritic pearlitic steel K55, there is a small amount of deep traps since the second loading is only slightly faster than the first one. The steel L80 has more traps, as this tempered martensitic steel is also more deformed than the ferritic-pearlitic steel K55. Consequently the diffusion coefficients are slightly lower. These results show diffusion coefficients for these steels as expected from the literature review. The welded ferritic pearlitic steel J55 has more traps. Consequently, the diffusion coefficient of the welded grade is even lower.

The welded steel K55 contains most traps and the diffusion coefficients are the lowest. The literature confirms that the values are within the typical range for carbon steels.

Usually, a low diffusion coefficient is favourable for hydrogen applications since a large number of deep traps hinders hydrogen to diffuse to zones with high stresses. Therefore low hydrogen diffusion coefficients represent more hydrogen resistant carbon steels.

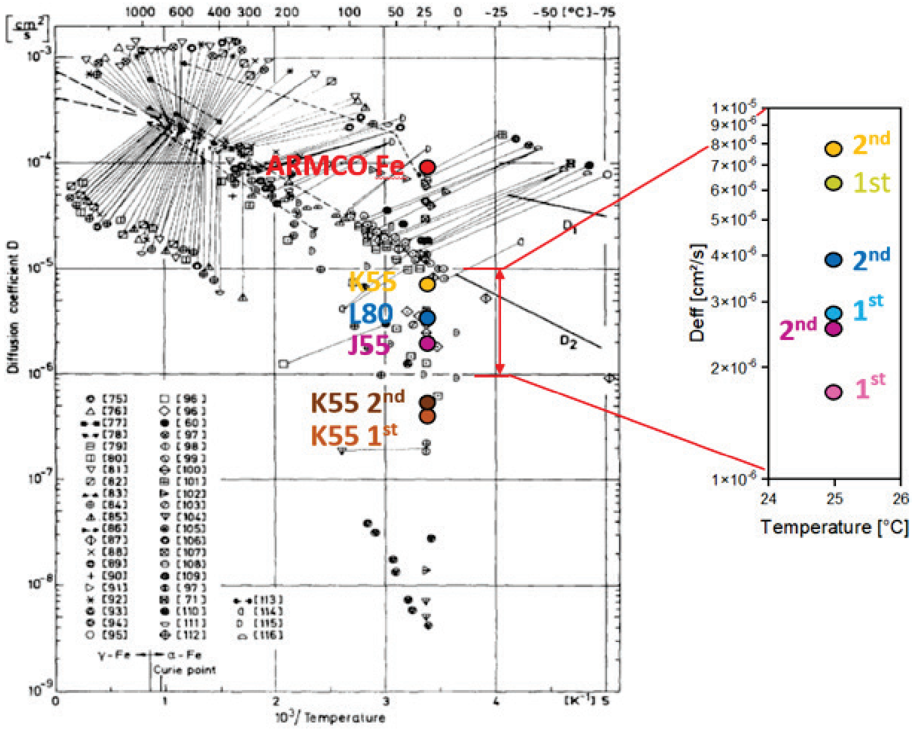


Figure 18: Overview of all investigated steel grades from which permeation measurements have been carried out.

Table 7: Overview of the values from the permeation measurements.

Material	D_{eff} [cm²/s]
K55 1st loading	$6.22 \cdot 10^{-6}$
K55 2nd loading	$7.96 \cdot 10^{-6}$
L80 1st loading	$2.68 \cdot 10^{-6}$
L80 2nd loading	$3.98 \cdot 10^{-6}$
J55 welded 1st loading	$1.69 \cdot 10^{-6}$
J55 welded 2nd loading	$2.36 \cdot 10^{-6}$
K55 welded 1st loading	$4.57 \cdot 10^{-7}$
K55 welded 2nd loading	$6.50 \cdot 10^{-7}$

With respect to corrosion rate in general, one can say that gases containing H_2S and CO_2 have the highest impact on corrosion rates. An electrolyte has to be present, so that the gases can dissolve and lower its pH value. There are some outliers in the corrosion rates for some materials (e.g. for the steel K55 at each gas, for the welded J55 at RT and 120 bar H_2, and for steel L80 at RT and 120 bar H_2 + 15 CO_2).

Table 8 shows the summary of results of localized corrosion attacks and cracking respectively for investigated materials:

Table 8: Summary of results of localized corrosion rates in Constant Load Tests for investigated materials.

Material	max H-uptake / blank value	Depth of localized corrosion attack*	cracking (no/yes)
20MnV5	2.71 / 0.11	≤ 5 µm	no
welded J55	2.95 / 0.65	≤ 5 µm	no
welded J55 pre-corroded	3.32 / 0.65	≤ 5 µm	no
welded J55 with notch	-	≤ 5 µm	no
K55	2.33 / 0.22	15 µm	no
K55 pre-corroded	3.64 / 0.22	≤ 5 µm	no
K55 notched	-	30 µm	no
welded K55	2.69 / 0.49	≤ 5 µm	no
L80	1.03 / 0.21	68 µm	no
L80 pre-corroded	3.55 / 0.21	15 µm	no
L80 notched	-	35 µm	no
P110	1.65 / 0.23	55 µm	no
quenched material	0.86 / 0.20	fracture	yes, in gas A and gas D
13%Cr	7.02 / 0.52	≤ 5 µm	no
316L supplier 1	2.04 / 1.94	no attack	no
316L supplier 2	4.53 / 3.20	no attack	no
Duplex 2205	7.02 / 4.72	fracture	yes, in gas D
Alloy 625	6.86 / 0.78	no attack	no

increasing yield strength (20MnV5 to quenched material)

increasing alloy content (13%Cr to Alloy 625)

* low...≤ 5 µm/mt * medium...5 – 30 µm/mt * high...≥ 30 µm/mt

* Table 8 shows the depth of localized corrosion attacks and cracking in a colour code as well. Green represents harmless or not significant localized attack (low or no danger of HE), while red and orange represent either cracking or deep localized attack that rather easily might result in failure (either by ongoing localized corrosion or by HE). The deepest localized corrosive attack was after exposure found in gas D consisting of H_2 and additionally H_2S and CO_2 atmosphere.

In Table 9 an overview of the applicability of all investigated steels for use in hydrogen storage is given.

Table 9: Applicability of investigated steels according to results of Constant Load Tests.

Material	Damage	Application with H_2S based on ISO 15156	Applicability in H_2 environment
20MnV5	no damage	Not specified	well applicable
welded J55	no damage	Acceptable for H_2S application for all temperatures	well applicable
welded J55 pre-corroded	no damage		
welded J55 with notch	no damage		
K55	no damage	Acceptable for H_2S application for all temperatures	well applicable when localized corrosion is not an issue
K55 pre-corroded	no damage		
K55 with notch	some localized damage		
welded K55	no damage	Acceptable for H_2S application if hardness ≤ 22 HRC	well applicable
L80	deep localized damage	Acceptable for H_2S application for all temperatures provided that it is type 1	applicable when localized corrosion is not an issue
L80 pre-corroded	some localized damage		
L80 with notch	some localized damage		
P110	deep localized damage	Acceptable for H_2S application only if T° > 80°C	applicable at RT when no H_2S is present
quenched material	failure in H_2	Not applicable	not applicable
13%Cr	no damage	Acceptable if pH_2S < 10.2 kPA	well applicable
316L supplier 1	no damage	Acceptable if pH_2S < 10.2 kPA	well applicable
316L supplier 2	no damage		well applicable
Duplex 2205	failure in (H_2 + CO_2 + H_2S)	Acceptable if pH_2S < 2 kPA	not applicable
Alloy 625	no damage	Acceptable for H_2S application for all temperatures	well applicable

increasing yield strength (20MnV5 to P110)

increasing alloy content (13%Cr to Alloy 625)

**no damage — **localized damage — **failure

**well applicable in hydrogen environment — **applicable in hydrogen environment when localized corrosion is not an issue — **not applicable in hydrogen environment

The applicability is indicated by a colour code in Table 9. Materials showing no cracking in constant load testing and no or very minor localized corrosive attack are considered as „Applicable". Materials showing localized corrosive attack although no cracking occurred in Constant Load Testing are considered as „Applicable with limitations". Finally materials that failed during Constant Load Testing are considered as „Not applicable". The tests were performed with different gas compositions and also at different temperatures. The tests with H_2S (gas C and D) were carried out with 1 bar of H_2S at 121 bar or with 1 bar of H_2S in 120 bar H_2 with 15 bar CO_2 at 136 bar in total, which can be considered as very severe condition compared to the ISO 15156 standard.

For more details on Constant Load Tests results, deliverable D4.6 can be consulted. In last deliverable D4.7, it was concluded that most materials except Duplex stainless steel 2205 are applicable under hydrogen storage conditions according to Constant Load Tests and Ripple Load Tests (that were performed in 2022). Although the absorbed hydrogen content is very high compared to the blank value of some steels, no local damage occurred. The research work done throughout the Hystories project (c.f. reports D4.1, D4.2, D4.3, D4.4, D4.5, D4.6 and D4.7) supports that the following steels can be used without any identified restrictions for hydrogen service, and in presence of wet environment and CO_2 (up to 15 bar) and in their application domain in presence of H_2S as specified in ISO 15156:

- CRAs
    - Alloy 625
    - 316L
    - 13 % Cr.
- Carbon steels
    - K55
    - 20MnV5
    - welded J55
    - welded K55.

Applicable with limits according to Constant Load Tests with respect to localized attacks are:

- Carbon steels
    - L80
    - P110.

Not applicable according to Constant Load Tests and the research work done throughout the Hystories project (c.f. reports D4.1, D4.2, D4.3, D4.4, D4.5 and D4.6) is:

- CRAs
    - Duplex 2205.

At last, in the deliverable D4.7, synthetized Hystories test program results and also existing standards in order to draw recommendations and propose some steel grades depending on the environment (external stress, presence of impurities, etc.).

2.5. Work package 5 - Modelling of the European energy system

The objective of this work package is to conduct an in-depth techno-economic assessment of the future scenarios for a widespread deployment of underground renewable hydrogen storage in the EU across the period 2025-2050. All the work has been performed by LBST, with some feedbacks or inputs on some hypotheses by Hystories' Advisory Board through several dedicated meetings and within the consortium. It consists of 6 tasks:

- Task 5.1: Definition of future scenarios for a widespread deployment of underground renewable hydrogen storage
- Task 5.2: Expected techno-economic requirements for underground renewable hydrogen storage
- Task 5.3: Adaptation of the model of the integrated energy system in Europe
- Task 5.4: Collection of relevant input data for scenario calculations
- Task 5.5: Techno-economic assessment of future scenarios for a widespread deployment of underground renewable hydrogen storage
- Task 5.6: Sensitivity analysis

Key modelling results of WP5 are summarized in the following. In total, four scenarios were developed (see Task 5.1) and analysed considering (a) different H_2 production pathway (domestic production vs. imports from non-EU regions) and (b) different H_2 storage technologies (salt caverns, storage in porous media and other aboveground H_2 storage possibilities). The analysis was conducted for the time horizons 2030, 2040 and 2050 as well as for 2025 as one additional simulation for one scenario run to calibrate the model. To ensure comparability the scenarios had the same hydrogen demand levels and GHG reduction targets (vs. 1990) of 37.5 % by 2025, - 55 % by 2030, -78.5 % in 2040 and climate neutrality by 2050. Hence, following 4 scenarios have been defined (also shown in Figure 19):

- Scenario A: mainly domestic H_2 production excluding storage in porous media
- Scenario B: mainly domestic H_2 allowing for all types of H_2 storage technologies
- Scenario C: larger H_2 imports from outside the EU excluding storage in porous media
- Scenario D: larger H_2 imports from outside the EU allowing for all types of H_2 storage technologies.

	Scenario A	Scenario B	Scenario C	Scenario D
General assumptions				
GHG emission reduction (vs. 1990)	(2025: -37.5%) | **2030:** -55% | **2040:** -78.5% | **2050:** -100%			
Hydrogen demand	Identical for all scenarios to ensure comparability			
Scenario differentiation				
Hydrogen production	**Mainly domestic,** limited imports	**Mainly domestic,** limited imports	Moderate domestic, **larger imports**	Moderate domestic **larger imports**
Hydrogen storage	**Salt caverns**	**Salt caverns, porous media**	**Salt caverns**	**Salt caverns, porous media**

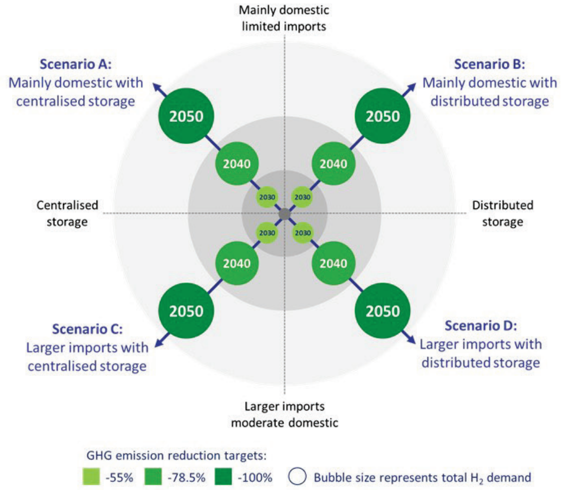


Figure 19: Scenario definition for energy system modelling in WP5 (Source: LBST)

Key results are that significant underground H_2 storage volume capacities are already needed in the short-term until 2030 with 20 - 40 TWh_{H2} (or 7 – 14 billion m³) also including first porous media sites. In the long term after 2030, the required storage volume capacities in the scenarios substantially grow up to more than (300 TWh_{H2} or 100 billion Sm³ in 2050) with an equal split between salt caverns and porous media. The capacities strongly depend on the overall hydrogen demand (1,700-1,900 TWh/a in 2050) both from different end-use sectors (industry, mobility and heating accounting for up to 90 % of total demand) and from power sector (i.e. re-electrification). Although potential storage capacities for pure hydrogen might be lower on TWh-basis in comparison to today's conventional natural gas (ca. 1,000 TWh_{CH4}), the need for geological reservoirs will be similar due to lower volumetric density of hydrogen. Moreover, both natural gas and hydrogen storage have the same ratio between volume capacity and demand of around 15-20 %.

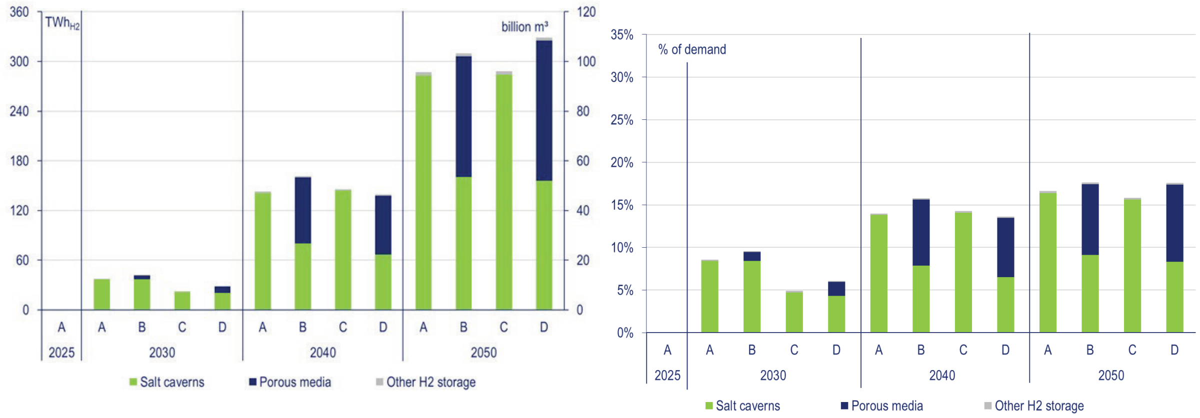


Figure 20: Optimal storage volume capacity in absolute values (left) and as percentage of overall hydrogen demand (right) in EU-27 & UK (Source: D5.5-2)

In the long term, porous media storage and salt caverns will both be operated at a seasonal basis with 1 to 2 full cycle equivalents per year, respectively. Nevertheless, salt caverns are expected to provide some short-term H_2 buffering to a limited extent, as this technology has a better technical capability to provide such services at lower cost in comparison to porous media. These results, however, are only based on an overall system view and does not take additional storage operation models like price arbitrage trading into account, which will additionally increase storage utilization. The injection flow rate capacity of underground H_2 storage of 180-250 GW (around 40 % - 60 % of installed electrolysis capacities) is lower by a factor of 2 in comparison to withdrawal flow rate capacities of 400-450 GW (ca. double size of installed capacities of H_2-fueled power plants). In this context, salt caverns are responsible for the major share of both input and output flow rate capacities and are, hence, used for hydrogen injection and withdrawal in large quantities at high speeds. These relationships fit well today's average design of underground storage sites for natural gas.

According to the results, most underground hydrogen sites are located in "six big" countries either with large H_2 demand or supply, namely in Germany, France, Italy, the UK, Spain and Poland, being responsible for more than 70 % of overall capacities in EU-27&UK. The country-specific split between the technologies is based on a cost trade-off between H_2 transport, volume and flow rate capacities and depends on technology availability (i.e., geological potential), the need for quick H_2 injection and withdrawal (the higher the larger salt cavern capacities) as well as requirements for storage volumes (the higher the quantity of stored H_2 at low flow rates the larger the porous media storage) in the given grid node. Further regional resolution has not been taken into account within this study. According to the modelling results porous media storage occurs mainly in Italy (up to 90 TWh depending on the scenario) followed by France (up to 28 TWh), Austria (up to 17 TWh) and Germany (up to 16 TWh) (see Figure 21).

Geographical distribution of underground H_2 storage sites is largely driven by hydrogen demand, infrastructure capacities and – to the largest extent – availability of storage capacities in the different countries. Scenarios with salt-caverns as only technology for underground storage show a higher concentration of available storage sites resulting in a less decentralized European underground storage system with higher infrastructure requirements between countries (see comparison of all four scenarios in Figure 22).

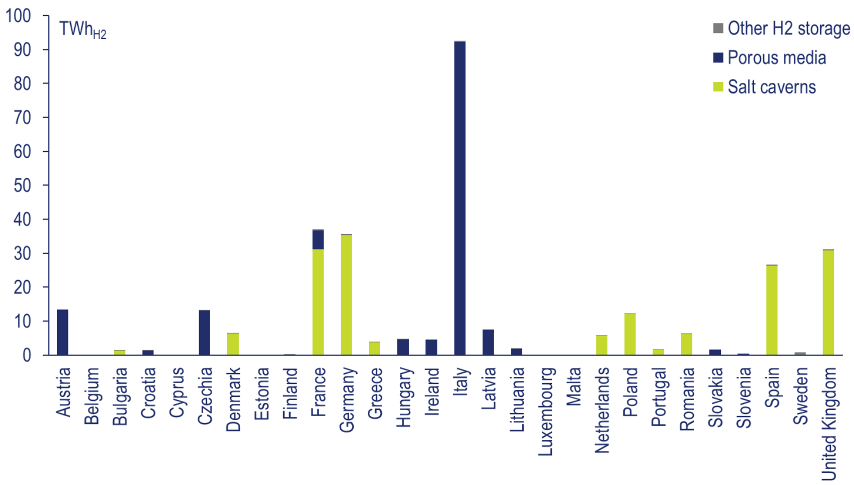


Figure 21: Optimal volume capacity for hydrogen storage (MS level, scenario B in 2050) (Source: D5.5-2)

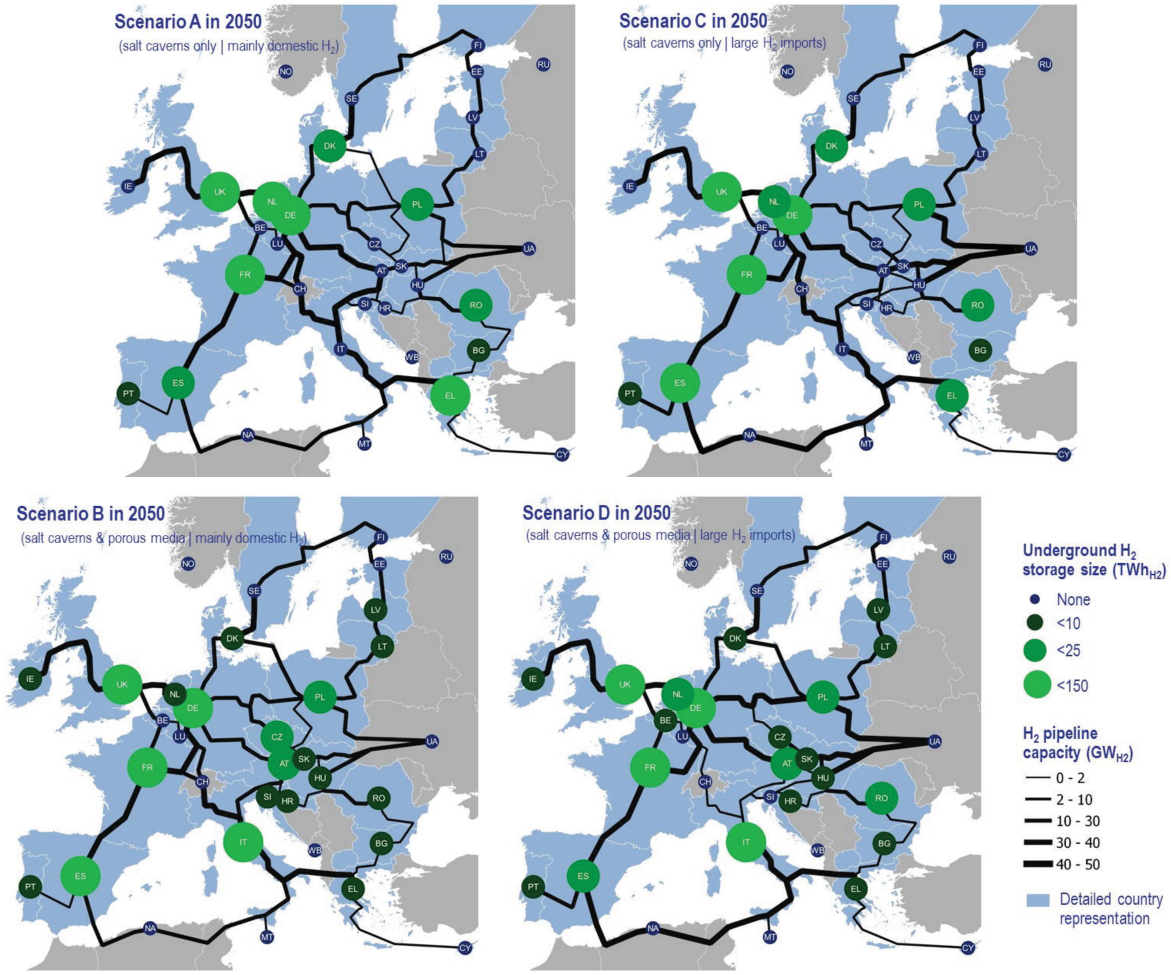


Figure 22: Underground H2 storage and pipeline capacitates on country-level in 2050 for all scenarios (Source: D5.5-2)

Sensitivity analyses were performed in Task 5.6 to check for robustness of modelling results against variations in key input parameters. Sensitivity analyses were completed in September 2022. Results are documented in D5.6-1. Analysis focused on Scenario B (salt caverns and porous media technology with high share of domestic production) for the year 2050 and were performed on EU27+UK and country level. Four key input parameters were identified in close cooperation with project's Advisory Board, namely:

- availability of volume capacities for porous media,
- storage efficiency for porous media,
- storage cost for (i) salt caverns and (ii) porous media, and
- hydrogen transport cost.

The sensitivities show nearly no impact of limiting porous media storage capacities from onshore & offshore to onshore only – especially at EU27+UK level. The main reason is that, although the overall capacity constraints for EU27+UK decreases from 18,737 TWh to 7,362 TWh, these limitations are still way above the actual capacities installed (145.7 to 147.5 TWh in porous media). In total, there are only three countries, where optimal volume capacities are reduced compared to the reference case ("Default value") where no effective limit is in place: Czech Republic, Ireland and Italy (see Figure 23).

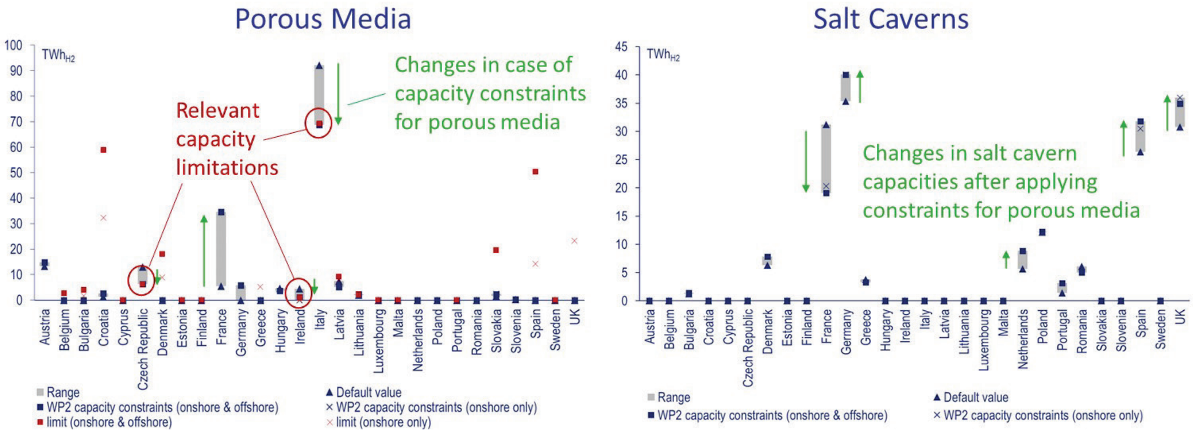


Figure 23: Sensitivity analysis for applying capacity constraints for porous media on MS level (Source: D5.6-1 (modified))

The higher the efficiency of porous media storage the more cost-competitive the technology and, hence, the higher the installed capacities. The volume capacity significantly varies between 110 TWh (95 % efficiency) and 170 TWh (100 % efficiency) on EU27+UK level, whereas only slight changes can be observed for the flow rate capacities. Accordingly, the demand for salt caverns decreases with rising efficiency – resulting in lower capacity requirements for salt caverns in countries like France or Germany.

The analysis of variations in storage cost reveals strong sensitivity of installed capacities in respect to storage cost. As salt cavern and porous media technologies are competing, the increase in cost of one technology leads to capacity reduction of the affected technology and capacity growth of the other technology. As a rule of thumbs a 50 % increase (decrease) of storage costs translates into ca. 50 % reduction (growth) of affected technology and ca. 50 % growth (reduction) of the competing technology on EU27+UK level.

Finally, the overall impact of H_2 transport cost on storage capacities and technology mix is very limited and ambiguous – at least on the system level for EU27+UK. As expected, high transport cost reduce overall H_2 flows and pipeline capacities between the grid nodes. Moreover, hydrogen transport is also used more efficiently at higher utilization rates. At the same time, the cumulative volume capacities and withdrawal flow rate capacities are larger for high transport cost to compensate the reduced energy exchange between the nodes by additional local storage services.

In summary, energy system modelling in WP5 confirmed the pivotal role of hydrogen technologies in futures energy system – especially for achieving long-term decarbonization targets. Until 2050, required electrolysis capacity were determined to be between 370 and 490 GW_{el} with an additional demand for underground hydrogen storage of 280-320 TWh. Still, already until 2030 a significant capacity of 20-40 TWh (around 7-13 million m^3) would be required in the cost-optimal energy system, even when considering each country as one grid node and consequently underestimating transport infrastructure limitations within each country. Due to long lead times of underground hydrogen projects of up to 10-12 years (incl. planning), this underlines the urgent need for building sufficient capacities in time. Finally, underground storage in porous media enables a broader geographical distribution of storage facilities across Europe and thus reduces curtailment volumes of renewables electricity as well as the need for hydrogen transport infrastructure between countries.

2.6. Work package 6 - Impact studies

Task 6.1 Assessment of the regulatory framework.

The starting point for this analysis of the legal framework for the underground hydrogen storage were the existing national regulations for the mature natural gas underground storage industry. The applicable legislation for underground hydrogen storage at the European scale is challenging since each country has its own laws pertaining to different areas of application (e.g., energy, mining, or environment), in its own language. To gather as much information as possible on the legal situation of underground storage of natural gas and hydrogen in the European context, the geographical boundary of the work is EU-27 + UK, a survey was launched to Hystories 7 partners and 17 third parties (so 24 institutions involved in hydrogen and/or underground storage from 17 countries), plus Hystories Advisory Board comprising 13 companies (large European gas storage operators, TSO, or manufacturers). The dissemination of the survey was supported by Geostock and CO2GeoNet, which made it possible to achieve the results: twenty-three entities provided relevant information for the study**.** The survey carried out by FHa, after an exhaustive literature review, consisted in 9 questions organised in 4 different sections: Survey Data, Regulatory framework, Standards related to the integrity of underground storages, and wells and Other related issues. Next Figure shows the breakdown of the 39 responses received per country (17 different countries).

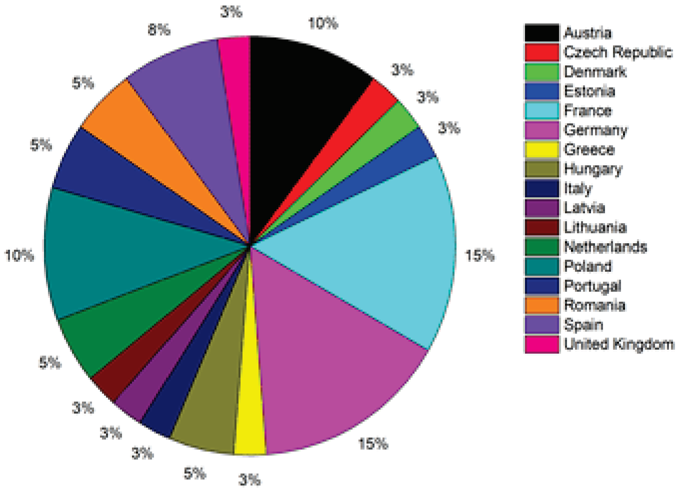


Figure 24. Percentage of responses obtained in the survey for each Member State. Source: FHa.

The **Deliverable D6.1 Assessment of the regulatory framework**, compiles the detailed legislation for the 17 countries shown in the previous Figure from the responses of national experts. In particular, the information provided concerns the legislation in force in each country for natural gas underground storage facilities, the bodies responsible for granting permits, the opinion on the need to adapt Directive 2012/18/EU[1] or other industrial safety standards applicable to hydrogen storage, as well as the existence of specific regulations for natural gas and, finally, the possible existence of hydrogen underground storage facilities that have gone through the permitting process.

Moreover, two different sets of standards related to the natural gas industry have been compiled. On the one hand, the standards developed by the International Organization for Standardization, ISO, for underground gas storage facilities, and on the other hand, different technical standards from usually international reference bodies or institutes, SMRI for instance for underground storage in salt caverns, in relation to the operation and safety of underground gas storage facilities.

In addition, to compile the complete list of permits required to develop a subsurface gas storage facility at present, **FHa prepared a questionnaire to complete the details of the permits by country**. This questionnaire was sent to the project partners to complete the information on their countries (GK-France, UP-Germany, MP-Poland) and filled by FHa in the Spain case. Once the information was completed by the partners, a review was carried out by members of the Advisory Board, belonging to these countries: France by Terēga, Germany by Storengy Deutschland and Uniper, Poland by Gaz System and Spain by Enagás. **Geostock disseminated the questionnaire to the partners and the Advisory Board** and as a result, four tables with details of the procedures have been developed.

Regarding the legal barriers identified, **FHa analysed all the information collected and all the barriers are explained in Deliverable 6.1.** Hydrogen is currently defined in most European regulations as a chemical product and not as an energy vector, which poses legal barriers to the development of business models based on renewable hydrogen as an energy vector. In this sense, the discrepancies at European level on the approach and on the allowed maximum concentration of hydrogen in the natural gas grid are an inherent barrier to the development of hydrogen as an energy carrier, whether to be injected into the existing underground gas grid or into a new pure hydrogen grid. On the other hand, regulatory barriers to underground hydrogen storage can be regional or national regulations that aim to curb any underground activity, not only exploitation but also exploration or geological characterisation. In addition, it has been found that in some Member States existing legislation does not cover underground storage facilities for the electricity industry. Finally, in some Member States the storage of natural gas can be decided independently of the claims of landowners. This is currently not possible for any other type of product, such as hydrogen, and represents a major barrier to underground hydrogen storage. The regulation that has allowed Europe to have a natural gas transport and storage network today needs to be reviewed and adapted to hydrogen.

In conclusion, a ranking of countries, shown in Table 10, according to the status of their UHS legislation has been generated.

Table 10: Legislation readiness, from D6.1

Current legal framework	Country
Legislation in force to UHS	Austria[1], Denmark, Germany[2], UK[3]
UHS legislation is under development	France, Netherlands
No UHS legislation under development	Czech Republic, Estonia, Greece, Hungary, Italy, Latvia, Lithuania, Poland, Portugal,[4] Romania, Spain[4]

[1] Only for scientific research
[2] Legislation in force for underground storage of chemical product, not specific UHS
[3] Long operation experience
[4] UHS named in national strategy

Regarding Task 6.2, FHa realized the analysis and comparison from an Environmental Life Cycle Assessment (E-LCA) perspective of two typical future large-scale UHS sites (salt cavern and porous media) located in France, identifying their hotspots (stages and processes). Required inputs corresponding to these typical underground storage sites in salt caverns and porous media were prepared by Geostock. In addition, a sensitivity analysis according to the origin of the electricity consumed during operation stage (H_2 storage) was considered, as well as a specific analysis of the CO_2 emissions of the UHS sites in relation to those of the H_2 production stage. Detailed life cycle inventory data were supplied by Geostock. These data were modelled in GaBi Professional software and complemented with data from Gabi 2022 database[2]. The Environmental Footprint (EF) 3.0 method[3] was applied to perform the E-LCA, selecting seven impact categories (climate change, acidification, freshwater eutrophication, marine eutrophication, photochemical ozone formation, minerals and metals resources use, and fossils resources use). The functional unit selected was the underground storage of 1 kg of H_2 produced through an electrolyser, stored for an annual cycle for both storage sites with a quality of 99.93 %, a pressure of 55-180 bar for salt cavern or 55-130 bar for porous media and a temperature of 40-60 °C. The system boundaries included the stages of construction, operation over 50 years and abandonment.

Regardless of the storage site, the operation stage (due to the high electricity consumption) was the main responsible for the potential environmental damage, but the construction stage has also had a significant impact (mainly due to the diesel use for machinery) (see Figure 25). The sensitivity analysis according to different electricity production mixes indicates that the environmental burdens could change substantially depending on the electricity origin. A comparison of both storage sites (see Figure 25) showed that the porous media analysed is the best option from an environmental perspective than the salt cavern in all categories except both resources use categories, due to the porous media stores 2.2 times more total kg of H_2 and consumes 1.7 times more electricity per kg of H_2 stored in operation stage.

The total scores obtained in this study for the climate change category (expressed in CO_2-equivalent emissions) for the construction stage, operation and abandonment stages of the salt cavern were, respectively: 235,000; 120,000 and -3,500 ton CO_2 eq., resulting in 351,500 ton CO_2 eq.; while for the construction stage, operation and abandonment stages of the porous media were, respectively: 216,000; 420,000 and -5,600 ton CO_2 eq., resulting in 630,400 ton CO_2 eq. The total scores of CO_2-equivalent emissions per FU for salt cavern and porous media resulting, respectively, in 0.281 and 0.229 kg CO_2 eq./kg H_2 stored. According to the literature[4], the CO_2 eq. emissions per kg of H_2 produced depending on different H_2 production scenarios (from electrolysis with high or low share of renewable electricity sources to steam methane reforming with or without carbon capture storage) were up to three orders higher (0-35.5 kg CO_2 eq./kg H_2)[4] than those got here, so UHS is not a H_2 value chain component with a high environmental burden compared to the H_2 production stage.

The detailed description of the impacts generated by the different stages of the theoretical storage sites analysed enables to understand the environmental footprint breakdown and develop solutions and alternatives to try to mitigate it. Thus, based on these conclusions, the energy efficiency and optimization in operation stage will be key factors to improve the global environmental performance of the future storage sites assessed.

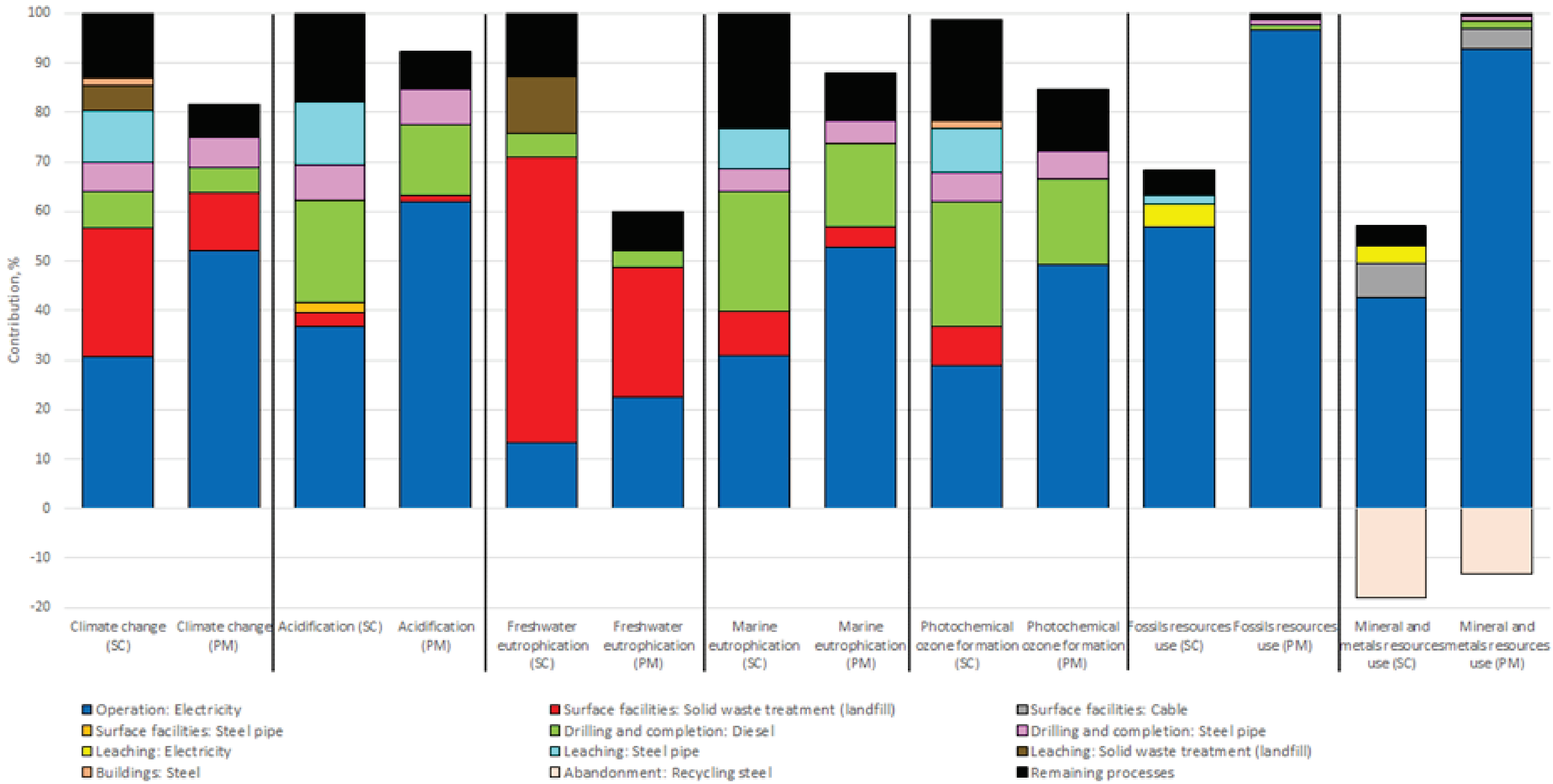


Figure 25. Contributions of main processes of salt cavern (SC) and porous media (PM) by impact category. Source: FHa.

Concerning Task 6.3 on the social impact analysis, FHa conducted study involving various groups of stakeholders in order to assess the potential social impact and public perception on the underground hydrogen storage concerning both salt caverns and porous media technology. The aim of this study was to evaluate the degree of technology acceptance and, by studying selected social themes, to identify potential social hotspots that might occur during the implementation of underground hydrogen technology and its possible impact on such group of stakeholders as workers, society and local community actors.

The social impact study has been divided into two main parts. The division has been realized based on the type of data collected, distinguishing secondary data, obtained with the use of software and databases and, on the other hand, primary data, obtained through questionnaires focused on public perception on underground hydrogen storage.

The first part of study based on secondary data has been conducted with the use of dedicated life cycle analysis software – openLCA[5] and with the implementation of PSILCA[6] - the Product Social Impact Life Cycle Assessment database. The database licence has been purchased and financed from the Hystories project grant. Five social impact indicators have been selected in order to characterise the social performance of the system. The selected impact categories available within PSILCA database include: fair salary (FS), weekly hours of work per employee (WH), fatal accidents (FA), gender wage gap (GW), contribution of the sector to the economic development (CE). The social hotspot screening has been performed for the sectors within Spain (ES) for the identification of social risks, hotspots and opportunities for and the most contributing processes within the system under investigation. The results of the social impact analysis present the highest contributions from the sectors under consideration to the selected impact categories. The results are expressed in medium risk hours or medium risk opportunity and are expressed per FU, being 1kg of hydrogen stored. The hotspot analysis showed that the sectors and processes from Spain connected with the highest potential social risk include construction, manufacture of machinery and equipment as well as collection, purification and distribution of water and land transport including transport via pipelines.

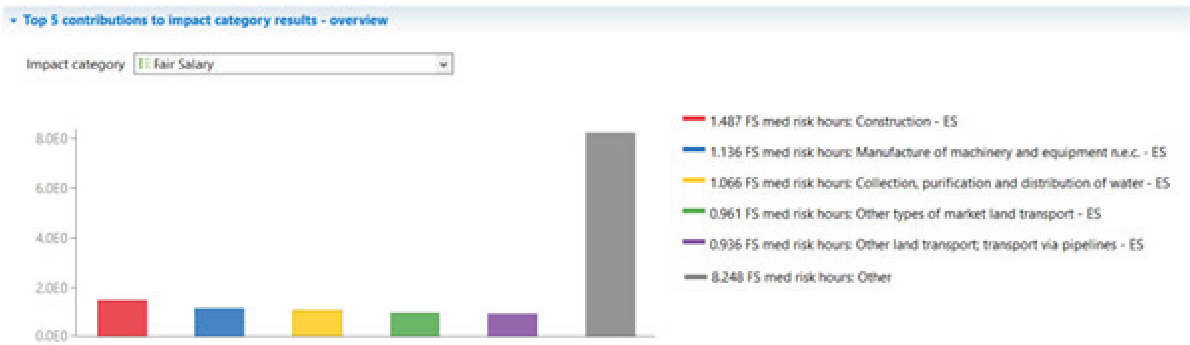


Figure 26: Selected results obtained using PSICLA database presenting UHS sectors´ social performance in the Fair Salary (FS) impact category in Spain.

Regarding second part of the study focused on primary data collection and public perception, two main groups of stakeholders have been taken into account. On one hand a tailored survey dedicated to project stakeholders, having deep understanding and previous experience related with underground hydrogen and gas storage has been developed by FHa and distributed among project experts and members of Advisory Board, using Microsoft Forms tool. On the other hand, a study focusing on general public has been prepared by FHa, together with Geostock´s involvement, and distributed via Voxco company specialized in conducting public surveys and market research.

A total of 13 answers have been collected after running the online survey dedicated to project stakeholders and experts having a previous knowledge, expertise and being familiar with underground gas storage, including hydrogen. The study conducted on the sample involving experts and project stakeholders, despite relatively low occurrence, corresponding to 2 out of 13 answers based on the survey conducted with project stakeholders, proved that there have been some cases where the deployment of underground hydrogen or gas storage sites have been affected by public pressure. The number of projects the 13 respondents have been involved in is however not known but is likely several hundreds. This has been mainly due to insecurity regarding possible negative effects of the new technology deployment and the local community preoccupation for environment. This study allowed to gather the key best practices and recommendations to alleviate the risk of possible delays or termination of project of similar character due to negative public opinion.

Concerning the study dedicated to general public, the total number of respondents taking part in this study includes 322 participants from Spain (106), France (111) and Germany (105) including respondents of all age groups and having different level of education.

The questionnaire has been constructed in a way for the interviewees to provide the answers based on the five-point scale, where, in most of the cases, the value 0 corresponded to worst performance and 5 corresponded to best performance, unless indicated otherwise. The questionnaire has been composed of 3 main sections, being: 1) Baseline questions; 2) Measuring awareness; 3) Influencing factors. The cumulated results representing the mean weight value based on the responses provided have been presented in the figure below.

Section	Question	Score
1 Baseline questions	Interest in the climate change	3,70
	General level of knowledge of renewable technologies	3,23
	The degree of belief regarding the contribution of renewable technologies to environmental impact reduction	3,39
	The degree of belief in the need of increasing the share of renewable energy	3,00
	Level of knowledge of energy storage	3,00
	General level of knowledge of hydrogen and hydrogen technologies	2,73
	Level of knowledge of underground storage technology	2,54
2 Measuring awareness	The degree of belief in the hydrogen´s potential for environmental improvement	3,36
	The degree of perception of hydrogen as a good alternative fuel	3,40
	Assessment of the perception related with risk associated with the implementation of hydrogen as an energy vector	3,11
	The degree of belief about hydrogen´s possible contribution to the reduction of reliance on fossil fuels	3,40
	Attitude towards underground hydrogen storage	3,22
	Rating of hydrogen storage technology as an alternative for other types of energy storage	3,24
	Perception related with safety of underground hydrogen storage technology	3,19
	The degree of belief in the underground hydrogen storage´s contribution to CO2 emission reduction	3,35
	The degree of belief in the underground hydrogen storage´s contribution to increasing the security of the European energy system	3,28
3 Influencing factors	Perception about the negative influence of traffic during the construction phase on the opinion about the deployment of UHS	3,04
	Degree of uncertainty related with underground hydrogen storage	3,07
	Perception of the contribution of the underground hydrogen storage site deployment on job creation	3,27
	Perception of the underground hydrogen storage´s contribution to the noise pollution during its normal operation	2,96
	Willingness to live in the proximity of an underground hydrogen storage site	2,79

Figure 27: Cumulated results representing the social themes divided into three sections investigated under the study dedicated to general public.

The results of the study conducted on the group of people representing general public, show that the biggest concern results from the deployment of new underground hydrogen technology in the vicinity of local community resident area. This is due to the common social phenomena referred to as “Not in My Backyard” syndrome which characterizes by the fact that people might be positive about some certain technology, however their attitude would change dramatically if this technology would to be implemented near their place of residence. Those results show the strong need to promote the hydrogen technologies among lay people and rising their consciousness related with energy storage. Special attention should be paid to increasing knowledge of underground hydrogen storage in salt caverns and porous media and its possible positive and negative effects on the society and local community including such factors as safety, pollution, opportunities including the job creation and general economic development.

[1] Directive 2012/18/EU of the European Parliament and of the Council of 4 July 2012 on the control of major-accident hazards involving dangerous substances, amending and subsequently repealing Council Directive 96/82/EC. OJ L 197, 24.7.2012, p. 1–37.

[2] Kupt, T., Baitz, M., Makishi-Colodel, C., et al., (2020). GaBi Databases & Modeling Principles 2020. Sphera Solutions GmbH, Leinfelden-Echterdingen Germany. https://gabi.sphera.com/support/gabi/gabi-6-lci-documentation/

[3] Fazio, S., Castellani, V., Sala, S., et al., (2018). Supporting Information to the Characterisation Factors of Recommended EF Life Cycle Impact Assessment methods. EUR 28888 EN, European Commission, Ispra, ISBN 978-92-79-76742-5, doi:10.2760/671368, JRC109369.

[4] Horizon Europe (2022). Clean H_2 Monitor 2022. https://hydrogeneurope.eu/clea n-hydrogen-monitor-2022/

[5] A. Ciroth ICT for the environment in lifecycle applications openLCA - a new open source software for life cycle assessment In t. J. Life Cycle Assess., 12 (2007), pp. 209-210, 10.1065 / lca2007.06.337, OpenLCA 1.9.0. (https://openlca.org).

[6] Ciroth, Andreas, and Franziska Eisfeldt. "PSILCA—a product social impact life cycle assessment database." Database version 1 (2016): 1-99.

2.7. Work package 7 - Ranking of geological sites

The key objectives as defined in Hystories Work Package #7 (WP) can be summarised as follows:

- To define a conceptual design with a focus on safe, affordable solutions to store hydrogen gas on a large scale (Task 7.1 – associated deliverable D7.1).
- To provide insights regarding underground storage development costs for the preselected sites (Task 7.2 – associated deliverable D7.2).
- To conduct a high-level Life-Cycle Cost Analysis (LCCA) for the preselected sites (Task 7.3 – associated deliverable D7.3).

Recall of the main basis and use of the parametric cost model (Tasks 7.1 and 7.2)

Task 7.1 was completed with the objective to set the foundations for a common understanding of the principles that govern the design, development, and construction of an underground storage site of hydrogen. Deliverable D7.1 covers the general engineering philosophy for the development and operation of an underground storage site of hydrogen in depleted fields, aquifers and salt caverns: it is based on a set of key assumptions that are deemed « reasonable » from an engineering point of view or that are derived from a statistical analysis (in particular for porous media with depleted fields / aquifers i.e. using worldwide databases for existing natural gas storages). In other words, the work carried out in Task 7.1 provides a high-level conceptual design that is not constrained by site-specific requirements or constraints.

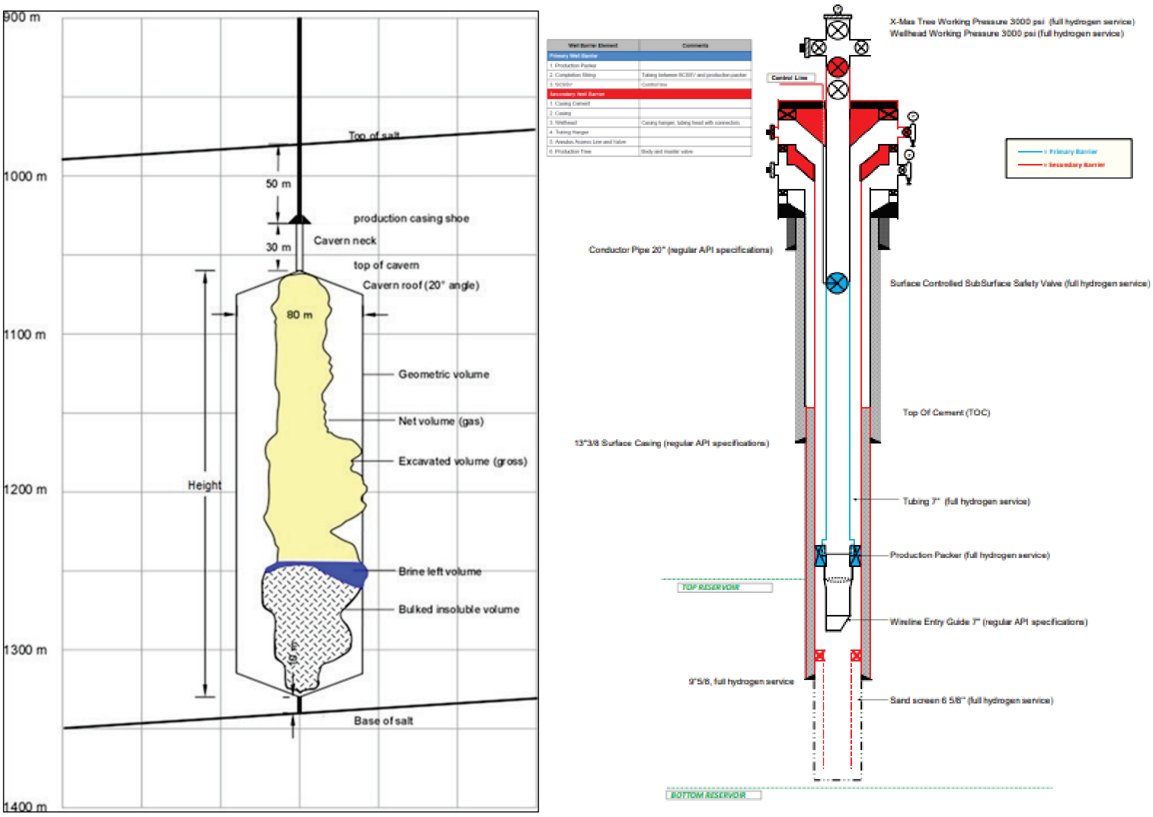


Figure 28: Example of the conceptual design main assumptions for a salt cavern (left) and a well completion (right). From D7.1-1

Deliverable D7.2 developed a simplified cost model based on the technical principles and key assumptions outlined in Task 7.1. In order to do so, a “bottom-up” approach was selected with the description of CAPEX, OPEX, ABEX breakdown with main cost leading parameters. The CAPEX, OPEX, ABEX estimates are based on factorisation on equipment and parametric model, with in-house data. This resulted in a Class 4 cost estimate as per the Association for the Advancement of Cost Engineering International (AACEi) Classification, leading to a ±30 % to 50 % accuracy. We note that not one, but 5 costs are given even for the typical designs, in order to capture various aspects of the cost estimation. Deliverability- and storage- based CAPEX; Fixed and Variable OPEX. Should it be applied to the typical design, the CAPEX per storage capacity is found at circa. 2 €/Nm^3, or 20 €/kg for both salt caverns and porous storages.

Table 11: Summary of the cost for the Typical design obtained in Hystories. From D7.2-2

COST RATE	UNIT	SALT CAVERNS	POROUS MEDIA
SUBSURFACE CAPEX RATE per working gas capacity	EUR per KWh_H_2(LHV) *[Range]**	0.51 *[0.44 – 0.69]*	0.20 *[0.11 – 0.45]*
SURFACE CAPEX RATE per withdrawal flowrate max. capacity	EUR per KW_H_2(LHV)	205	645**
VARIABLE OPEX RATE per cycled quantity For COE = 60 EUR/MWh	EUR per MWh_H_2(LHV)	2.25	3.83
FIXED OPEX RATE*** % of related CAPEX / year	% Surface CAPEX / year	3.7%	3.7%
	% Subsurface CAPEX / year	0.4%	1.5%

The above values have notably been used for salt cavern and porous media storage cost in WP5 during RP2. One of the results obtained by this Energy modelling work package are the cycles for both types of storages the enable the minimum cost for the overall energy system

It should be noted that the CAPEX obtained by Hystories has been benchmarked by very visible works outside of the Hystories project during Reporting Period 2:

Table 12: extract of IEA Hydrogen TCP-Task 42, 2023 report[2] showing Hystories CAPEX results compared to available public cost estimates (left) and boundary limits of these (right). Same is available for porous media.

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	€/kgH_2	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 H_2	8 x 2,635	4,000		1,912		500
Withdrawal to injection ratio	-	2.0	1.0		1.7		Assumed 1
Withdrawal cap.	ton H_2/day	8 x 23	259		118		50

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

Hystories is the only reference that has split the CAPEX related to the energy stored (in €/MWh) to the CAPEX related to the deliverability of the storage (in €/MW of discharge power capacity). When combined for the basis of design of each sources, results can be compared, although both basis of design and boundary limits are often different.

Ranking of sites (Task 7.3)

Based upon the estimations of the underground storage capacity in Europe from Hystories' D2.2 for depleted fields and aquifers and from Caglayan *et al.* (2020) with few adjustments for salt caverns, the identified onshore technical capacity is several orders of magnitude higher than the underground storage demand as found in Hystories WP5 (D5.4) for both salt caverns and porous media:

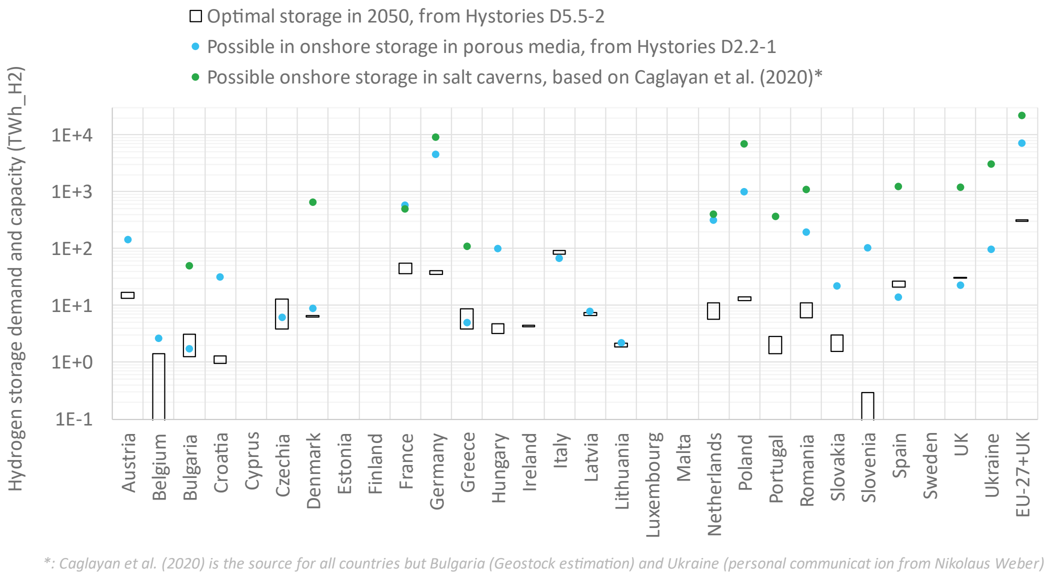


Figure 29: Optimal storage capacity in EU-27+UK+Ukraine in 2050 (scenarios B and D of WP5) and technically possible onshore storage capacity in Porous Media and Salt caverns. From D7.3-1

2 Hydrogen TCP-Task 42 (2023), "Underground Hydrogen Storage: Technology Monitor Report", 153 pages including appendices.

This implies a need for ranking the possible underground hydrogen storage sites in Europe.

An underground storage is not an off-the-shelf manufactured product. Most notably, its capacity and the technical risk in developing it are site-specific. The development cost is site specific as well, but also depends on the cycle the storage is designed for. Hystories developed ranking marks to capture this.

- As other geology-related activities, underground hydrogen storages depend on the geological conditions found on site.
  - When the site-specific geological conditions are known, engineering solutions are specifically designed and this reflects in a specific development cost. For instance, the depth of the storage has a large impact. Hystories D7.3-1 introduced a **Levelized Cost of Storage (LCOS) mark** that is applied to relevant and known subsurface specificities.
  - When the site-specific geological conditions are uncertain, when there are residual risks associated to them or when mitigations cannot be fully identified, it impacts the suitability or readiness of the development of the underground storage. For instance, the impact of microbiological activity in porous media at reservoir scale is hard to evaluate today. Hystories D7.3-1 introduced a **suitability mark** to reflect the technical readiness and level of technical risk given the available knowledge for developing a hydrogen storage.
- In addition, underground storage facilities are cycle-specific: for a given storage capacity, sites being able to inject the full capacity in 1 week or in 3 months are not the same. The sizing of above ground facilities especially (compressors, dehydration units) is directly impacted, and subsurface facilities might also be affected: e.g. number of wells of a porous media storage. This work has introduced **two operational cycles, a seasonal and a fast** one derived from WP5 results, to cover the range of cycles where underground hydrogen storage is the most expected.

These marks have been computed for 805 porous media traps, 18 bedded salt deposits and salt domes found in EU-27+UK+Ukraine. All results are given in D7.3-1. As an example, the Levelized cost of storage are given for either seasonal cycles, per country (Figure 30) and per capacity (Figure 31). The same is available for fast cycles in D7.3-1.

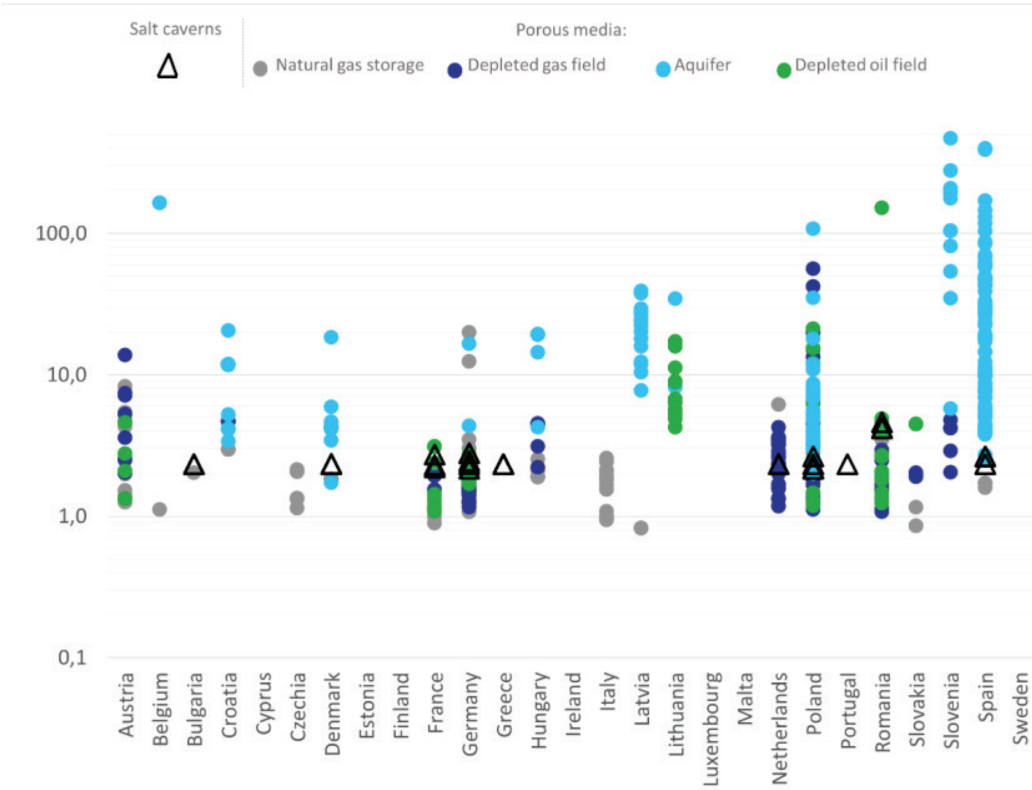


Figure 30: LCOS for porous media and salt caverns, Operating Cycle 1 (seasonal), per country. From D7.3-1

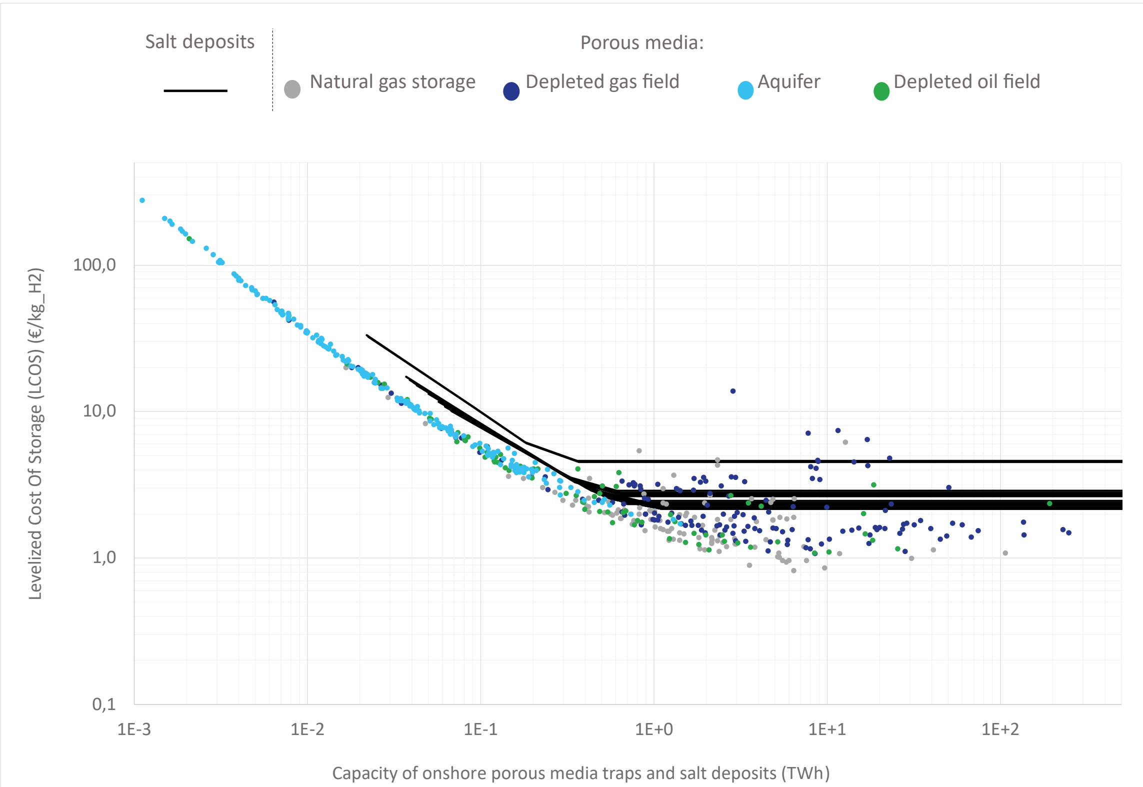


Figure 31: LCOS for onshore porous media and salt caverns in EU-27+UK+Ukraine, Operating Cycle 1 (seasonal) per capacity. For porous media (dots indicate the maximum capacity of the trap) and for salt caverns (size to be chosen by design on the solid line). From D7.3-1

The Analytical Hierarchy Process was applied to define a Suitability mark and applied to all the porous media traps to identify the most suitable storage opportunity between salt caverns and porous media traps. Seven criteria were used in the analysis: the lithology of the seal, its estimated minimum thickness and lithology, the existing faults and number of abandoned wells, the lithology of the storage and its readiness level (estimated time to market), and the microbial risk. The suitability mark is given per capacity in Figure 32 and per country in Figure 33.

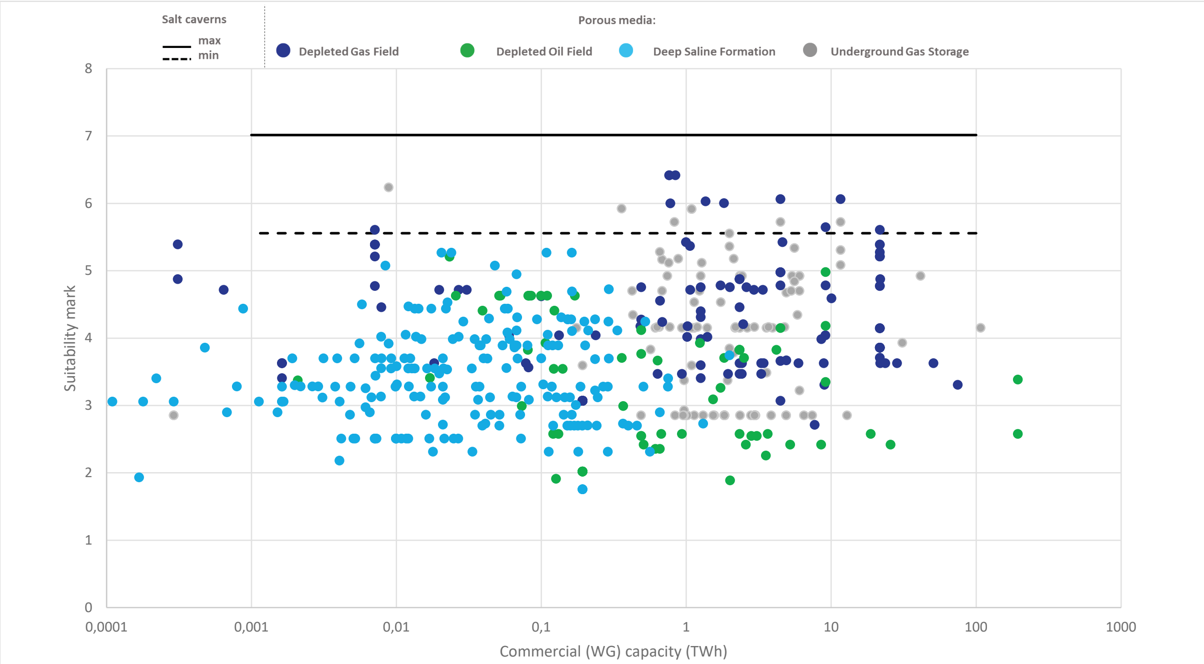


Figure 32: Suitability mark of traps based upon the commercial (Working Gas) capacities. From D7.3-1

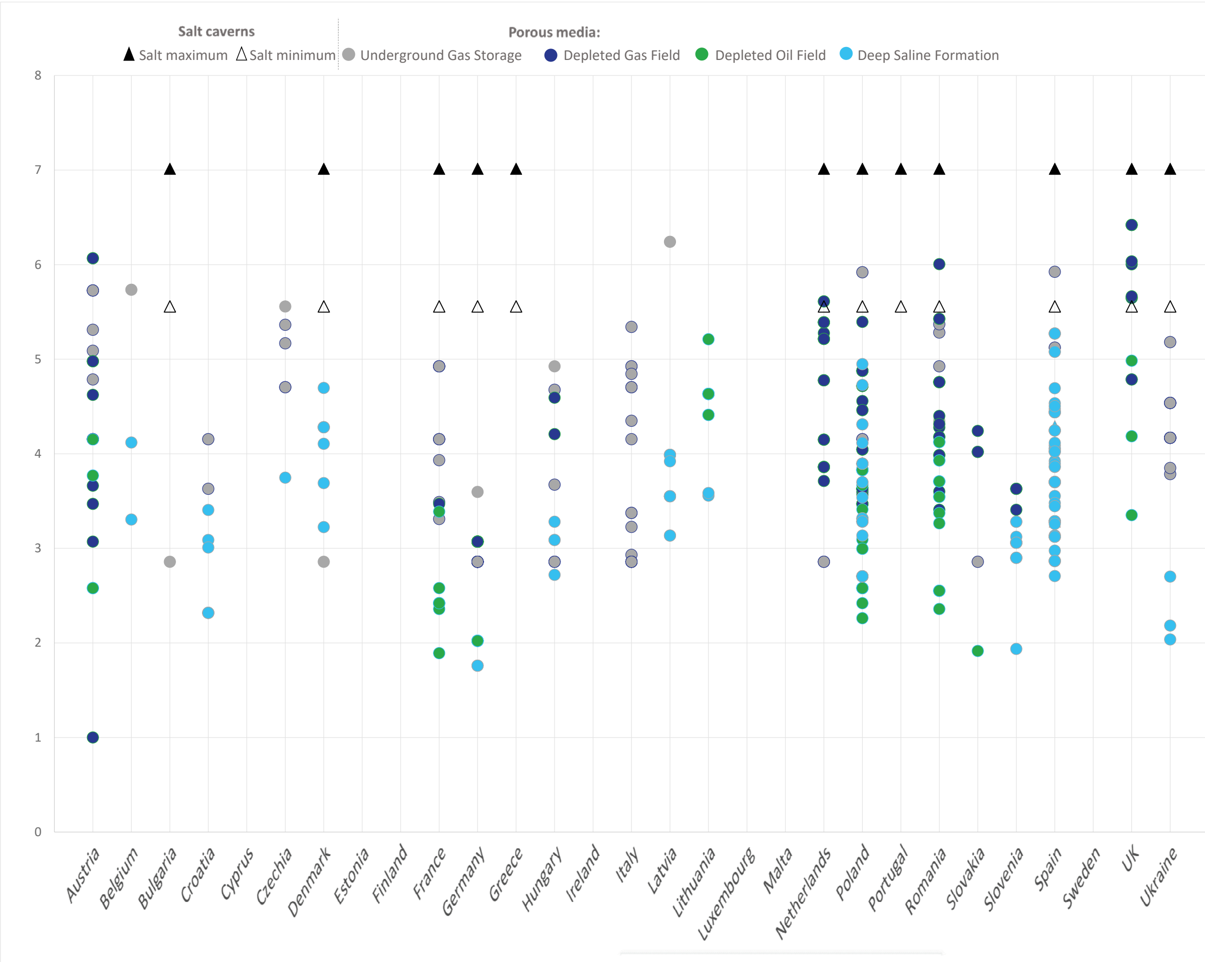


Figure 33: Suitability mark of traps per country. From D7.3-1

The main conclusions we can draw from this ranking are the following:

- The Levelized Cost Of Storage (LCOS) Increases significantly when the storage site capacity is smaller than the values considered for the Conceptual design (D7.1-1): 250 MM Sm^3 capacity site for salt caverns (21 000 tons; 0.7 TWh) and a 550 MM Sm^3 capacity for porous media (46 000 tons, 1.5 TWh LHV).
- **For seasonal cycles, the LCOS is 1.1 €/kg (32 €/MWh; 90 k€/$MMSm^3$) for aquifers and depleted fields; 2.3 €/kg (70 €/MWh; 200 k€/$MMSm^3$) for salt caverns[3]**. Porous media are found significantly less expensive than salt caverns. This is consistent with the current natural gas storage industry, dominated by seasonal cycles and where most capacity is found in porous storages.
- **For fast cycles, the LCOS is 2.6 €/kg (77 €/MWh; 216 k€/$MMSm^3$) for aquifers and depleted fields; 2.0 €/kg (59 €/MWh; 170 k€/$MMSm^3$) for salt caverns[3].** Costs of both technologies are found to be close. Such opportunities of fast cycle storage at relatively low cost in porous media correspond to reservoirs with particularly favourable characteristics.
- The suitability marks of salt caverns are found significantly higher than those of porous traps, reflecting the relatively higher maturity and the lower technical risk, notably related to the microbiological activity. **From the suitability mark point of view, the salt caverns, and then the existing natural gas storages and depleted gas fields offer the best opportunity for the creation of underground hydrogen storages.**

These general conclusions are given at European scale. It does not account for the opportunity of developing a storage a given location. Country-level results can be drawn based on the data presented in the above sections 3 and 4. Project level requires to identify the location of a storage opportunity within a country. This is the purpose of the WP9 of Hystories.

[3] The figures correspond to the weighted average cost of developing the cheapest sites of EU-27+Ukraine+UK in either salt or porous media until the maximum demand (325 TWh of underground hydrogen storage capacity in 2050, from WP5 results) is reached.

2.8. Work Package 8 - European Case Studies

The main objective of the WP8 is to assess the feasibility of implementing large-scale storage of renewable hydrogen in depleted gas fields and other types of geological stores at selected sites in the European Union. This assessment will be based on detailed case studies for selected Member States and sites. Thus, the specific objectives of this work package include:

- **T8.1**: Development of a joint methodology providing a consistent toolbox for all case studies enabling their techno-economic comparison. Resulting Deliverable: **D8.1**.
- **T8.2**: Identification of potential business cases for the use of large-scale underground renewable hydrogen storage at potential sites in selected Member States. Resulting Deliverables: **D8.2 – 6**.
- **T8.3**: Comparison of different European case studies to obtain common conclusions about the profitability of the technology. Resulting Deliverable: **D8.7**. The work has been done by FHa.

Deliverable D8.1 covers the joint methodology which was developed taking the current underground natural gas storage business models as main reference. The proposed business model is based on the underground storage service provided by a generic gas operator for third party companies interested in storing their own hydrogen. The methodology does not consider the production of renewable hydrogen from each country renewable resources, but it does consider the storage service and its related revenues according to the annual hydrogen throughput of the storage site. Given the techno-economic differences existing between a salt cavern and a porous media, two different models were built for the business cases analysis, one for each type of underground hydrogen storage, and implemented as toolboxes in Excel. Once defined the potential case scenario by introducing a selected set of parameters, the Excel tool allows to evaluate the viability and profitability of a specific business case through the cash flows analysis. Therefore, the user can modify several economic parameters to generate a proper business case. Among them, the user will choose a potential subsidy, the venture period (set to 30 years as default value), the residual value of the overall plant at the end of the venture period, the hydrogen storage price, corporate taxes, the discount rate, and consider subsidies and/or financing funds during a certain period, with interest's calculations included.

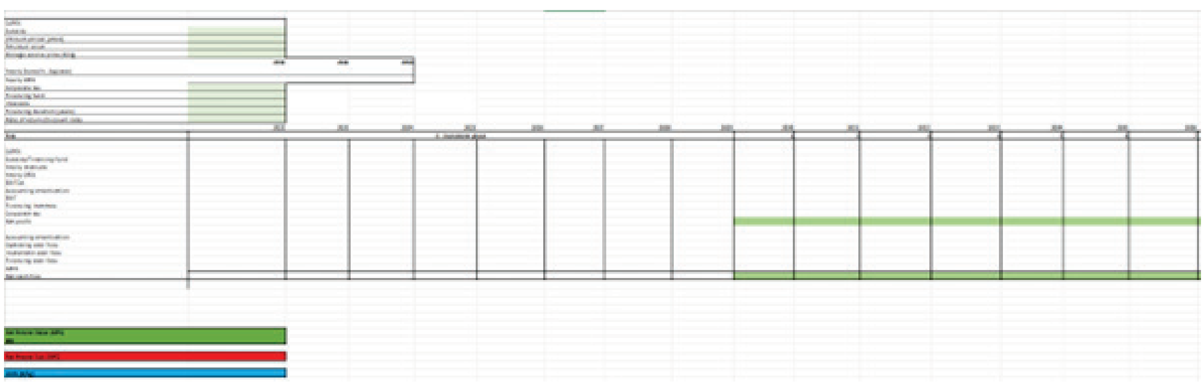


Figure 34. Cashflow analysis spreadsheet included in the toolbox. From D8.1

Once defined the joint methodology in T8.1, 5 potential business case studies have been carried out, hypothetically located in France, Germany, Spain, Poland and Italy. Geological site and storage site design has been sized taking as reference the MID scenario presented in Deliverables D7.1 and D7.2, adapted to market conditions if appropriate (e.g. for Germany). To facilitate future benchmarking of the cases in the next Task 8.3 of the project, a set of common parameters have been established for all the case studies, with the objective of creating a common reference baseline. The baseline scenario is characterized by a Net Present Value (NPV) of zero (NPV=0), which was achieved by adjusting the storage service margin profit (%) applied to the H_2 storage cost, which was initially assumed to be equal to the levelized cost of storage (LCOS). In Deliverables D8.2 – 8.6, a comprehensive analysis for each business case is provided, including a detailed description of the specific site costs breakdown and a sensitivity analysis, all with the objective of optimizing the economic feasibility of the business venture.

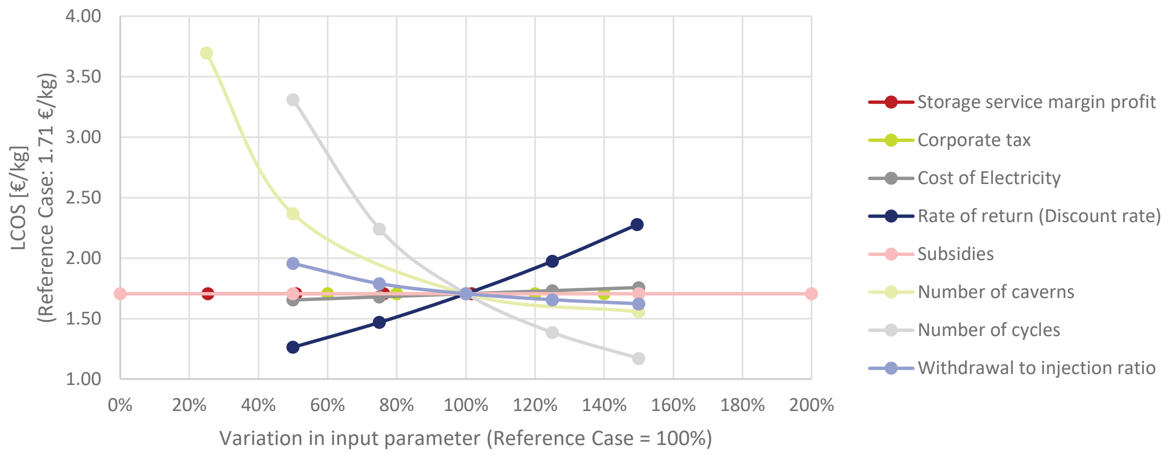


Figure 35: Effect of key parameters on LCOS as result of sensitivity analyses for the German business case. From D 8.3

Finally, Deliverable D8.7 will gather the outcomes resulting from T8.3, including the benchmarking of the selected Member States business cases, consolidating and aligning the results, as well as drawing conclusions on the profitability of the technology at single sites for large-scale underground hydrogen storage in Europe. The content presented in D8.7 aims to facilitate a straightforward comparison among the EU business cases formulated in T8.2, focusing on storage potential, regulatory framework, cost analysis, and associated financial aspects.

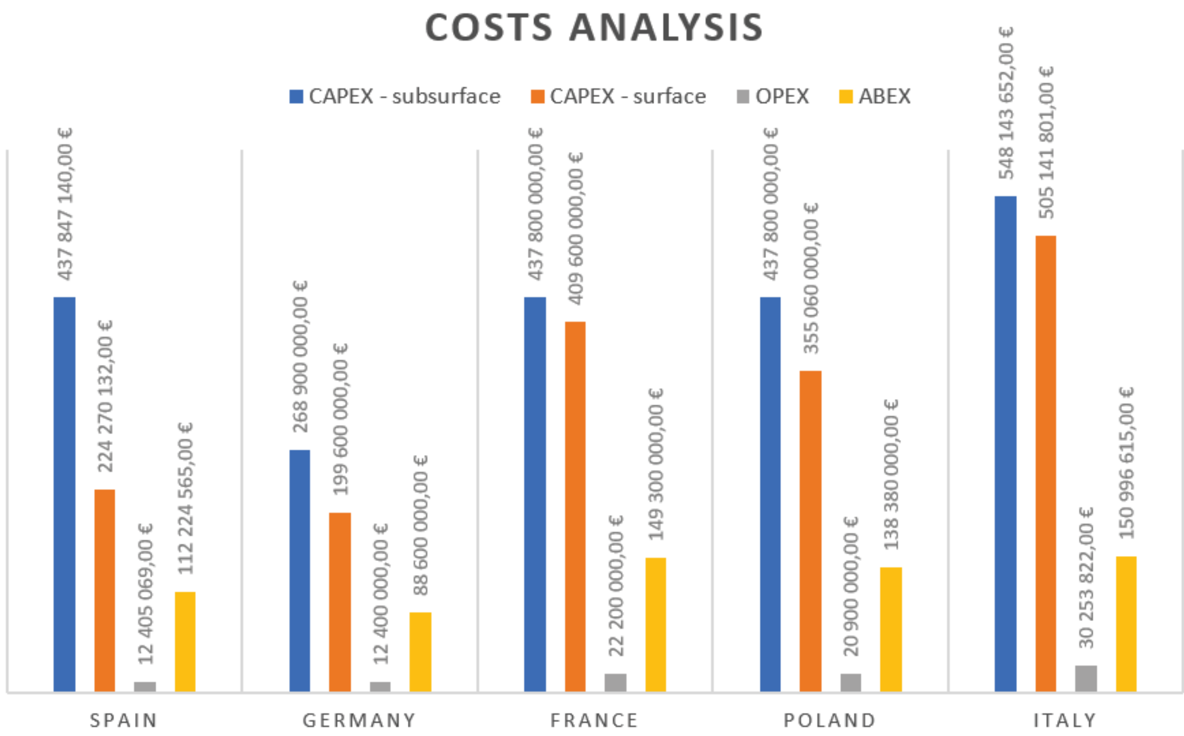


Figure 36. Cost analysis for each business case. From D8.7

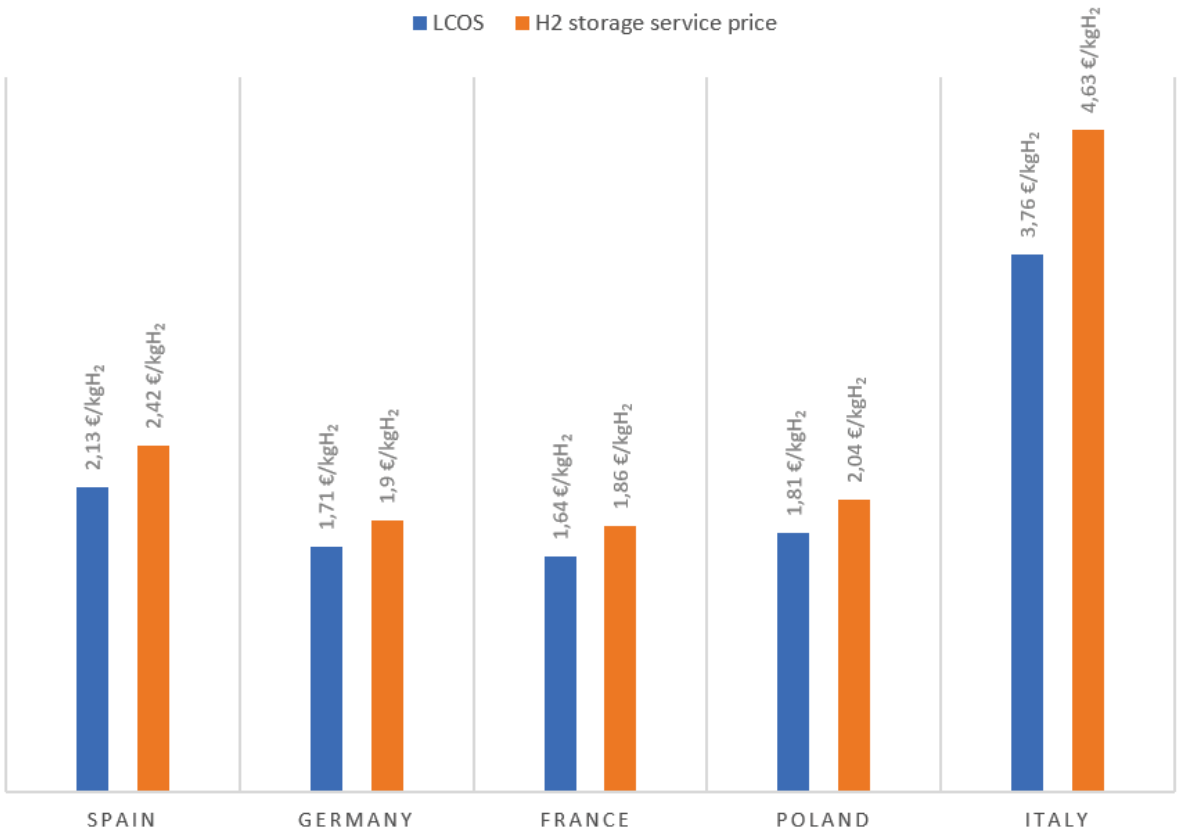


Figure 37. Levelized Cost of Storage (LCOS) and H_2 storage service price resulting from each business case. From D8.7

3. Hystories work package within the State of the Art

Hystories work on underground hydrogen storage is bringing new developments in a field also developed by many other projects, companies and institutions. For instance, Hydrogen IEA TCP-Task 42 (2023) provides a very good overview of the current state of the art and list of ongoing research projects and pilot demonstrators.

A simplified and synthetic view of Hystories' work in this context of very active technical and socio-economic developments around UHS is given in the tables below. Recommendations for actions given in the Executive Summary are also recalled, to trace the WP they originate from.

Table 13: Hystories main technology development results in their context, gaps and call for actions

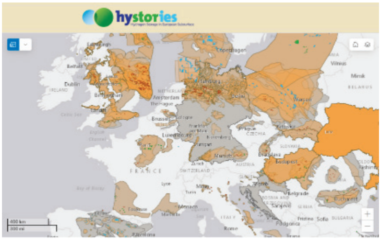
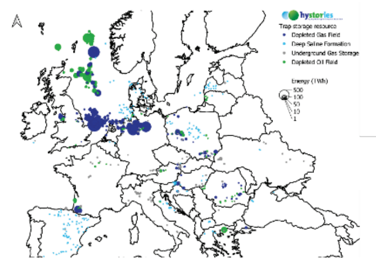
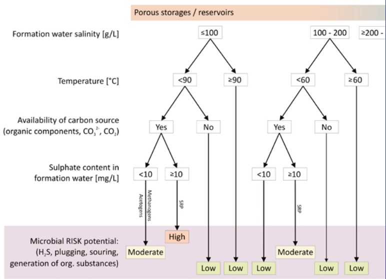
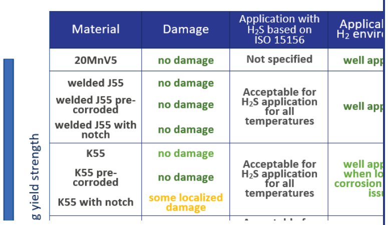
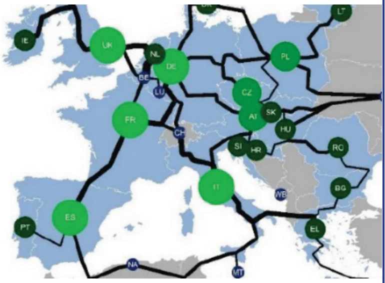
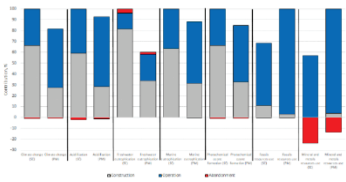
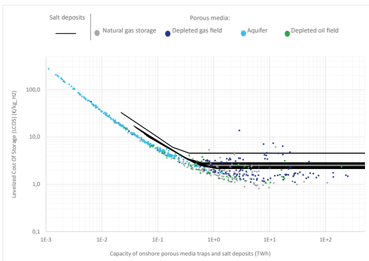
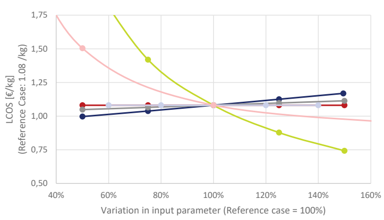
	Summarized state of the Art	Hystories main development - Summary	Gaps and calls for action
WP1 Geology	• No hydrogen storage Europe-wide public info database • European scale CO2Stop, ESTMAP databases, not focused on hydrogen • Usually not coupled with (latest) salt deposit databases	• Unified database + GIS collating available geological data on reservoir and seal characteristics for depleted fields and saline aquifers at European scale (D1.3) +SMRI salt deposits data 	• 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 Hystories' database
WP 2 Reservoir engineering and capacity estimation	• Porous storage capacity estimations based on the sole conversion of existing natural gas underground storages. Aquifers and depleted fields are not included. • Technical capacity estimation for salt (Caglayan et al. 2020)	• P10, P50 and P90 Capacity estimation for 800+ storage traps, onshore and offshore 	• Storage performance for porous UHS needs industrial reference (mixing…) à Call for Field scale porous UHS • Dynamic capacity estimation was done for 22 traps but required for better characterization and capacity estimation
WP3 Cost estimation and site ranking	• Hydrogen known to be a very strong reductor, but reaction are inhibited below 200°C in abiotic conditions • Biotic reactivity known to happen from Town gas and pilots. Characterized at laboratory scale (cf. e.g. Thaysen et al., 2021)	• Large brine sampling, microbiological characterization and testing program • Risk assessment flowchart (D3.2) 	• 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 dpvt and validation based on at scale porous UHS observations → Call for pilots over 10+ years
WP4 Material and corrosion	• Wells are a UHS' main man-built structure • Standards exist, developed by and for the O&G industry (API) • Hydrogen raises new questions (embrittlement…) • Standards exist for H_2 in surface applications • There is no applicable standard for H_2 wells !	• Extensive experimental program to analyse the behaviour of steel grades under conservative hydrogen storage conditions • Practical recommendations: 	• Increasing number of references but still no standard for well casings → Call for standardisation • Wellhead, SSV, packer etc. also need to be covered → Call for involving equipment Manufacturers • Wells are not all new. → Call for a re-qualification procedure

Table 14: Hystories main socio-economic results in their context, gaps and call for actions:

	Summarized state of the Art	Hystories main development - Summary	Gaps and calls for action
WP5 Impact studies	• Analytical analyses of storage drivers and of offtakers needs • European scale deployment plans (not quantified regarding storage capacity need) • Scenario-based and assumption-based projections of future hydrogen storage demand	• scenarios and hypotheses definition • EU-scale energy system modelling (D5.5) • Techno-economic assessment result and sensitivity study (D5.6) 	• Call for comprehensive analysis, incl. « societal benefits » externalities (e.g. energy independence) • Call for regional spatial resolution energy modelling
WP6 Permitting readiness, Environmental footprint Public perception	• 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	• EU-scale regulation review (D6.3)  • Reference Carbon footprints (D6.3) • Stakeholders and general public survey in 4 countries (D6.4)	• Call for « Administrative experiment » through pilots • Call for comparison of UHS with alternative technical options • Call for actions promoting societal information
WP7 Cost estimation and site ranking	• Public sources of UHS cost gave capacity-based costs (€/MWh), never deliverability-based (€/MW) • No obvious way to rank possible sites	• Development of a H_2-specific cost model with clear boundary limits for both salt & porous media (D7.2) • Application to 800+ traps and salt deposits (D7.3) 	• Call for sharing the data from industrial pilots and projects • Call for setting H_2 grid specifications and techno-economic study of the gas treatment
WP8 Storage market conditions	• No existing experience with UHS business plan • Experience of business frames for geopolitical reasons (oil), Seasonality demand fluctuation (nat. gas), Logistical / feedstock buffer (LPG, H_2)	• Analysis of the storage market and business model application for 5 countries, sensitivity study (D8.2-7) 	• Call for investigating and setting business options to support first projects • Call for deployment planning / regulated frames especially for strategic storage (cf. oil storage experience)

4. References

GuideHouse, 2022. European Hydrogen Backbone. A European hydrogen infrastructure vision covering 28 countries. April 2022. Available at www.ehb.eu

Heidug, W. (2013). Methods to assess geologic CO2 storage capacity: status and best practice. International Energy Agency Workshop Report.

IEA Hydrogen TCP-Task 42 (2023) "Underground Hydrogen Storage: Technology Monitor Report", 153 pages including appendices.

Luboń, K., & Tarkowski, R. (2020). Numerical simulation of hydrogen injection and withdrawal to and from a deep aquifer in NW Poland. international journal of hydrogen energy, 45(3), 2068-2083.

Luboń, K., & Tarkowski, R. (2021). Influence of capillary threshold pressure and injection well location on the dynamic CO_2 and H_2 storage capacity for the deep geological structure. International Journal of Hydrogen Energy, 46(58), 30048-30060.

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Acknowledgment

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under grant agreement No 101007176.

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