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Hystories project – Hydrogen Storage in European Subsurface: main project outcomes and applications for the underground gas storage industry

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Abstract

The Hystories project (www.hystories.eu) explored Underground Hydrogen Storage (UHS) potential in Europe and gathered geological data from 23 countries. The project was funded by the European Union via the Clean Hydrogen Partnership from 2021 to 2023, bringing together 24 companies, universities and research institutes from across Europe.

The Hystories project aimed to advance understanding of the technical aspects of UHS to support development in Europe. The project identified potential underground hydrogen storage sites in porous media and estimated their total hydrogen storage capacity at 6,850 TWh (19,000 TWh including offshore sites) in the EU and neighbouring countries, to be compared with the already published technical capacity of 13 800 TWh in onshore salt deposits (or 64 400 TWh including offshore sites). A risk analysis method associated with microbial activity in future underground hydrogen storages was proposed covering both salt cavern and porous media H2 storage. A dozen common steel grades for storage wells were tested for their durability when exposed to hydrogen, and recommendations were issued on the type of steel to be used in transport and storage projects.

The Hystories project also provided technoeconomic assessments to support planning for deployment of UHS in Europe. The project proposed parametric and hydrogen-specific cost models of typified storage site developments (salt cavern and porous media) and proposed reference environmental footprint assessments over the life cycle of a plant. Through an economic optimization of the cost of the future European energy system, optimal hydrogen storage cycles and storage capacity demand per country for either salt cavern and porous media were assessed. A high-level estimation was produced for the cost of developing salt domes, 18 bedded salt deposits, and 800+ porous media traps throughout Europe.

Key words: Hydrogen storage, salt caverns, aquifers, depleted fields

Introduction: case for underground hydrogen storage

Green hydrogen is a clean and renewable energy vector when generated with low-carbon renewable energy. The use of this gas as an energy carrier could transform the sustainability of the industry and mobility sectors. Hydrogen transportation and underground storage infrastructure can make renewable energy available when and where offtakers need it, i.e. usage driven by demand and not by production. Green hydrogen generated using renewable energy sources could be one of the pillars of the future European energy and transport systems, making a major contribution to the european transformation to a Net-zero economy by 2050, in line with the European Union (EU) RePower-EU plan. Underground Hydrogen Storage (UHS) targets salt caverns, depleted hydrocarbon fields, 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: CO_2GeoNet, Fundación para el desarrollo de las nuevas technologĺas 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.

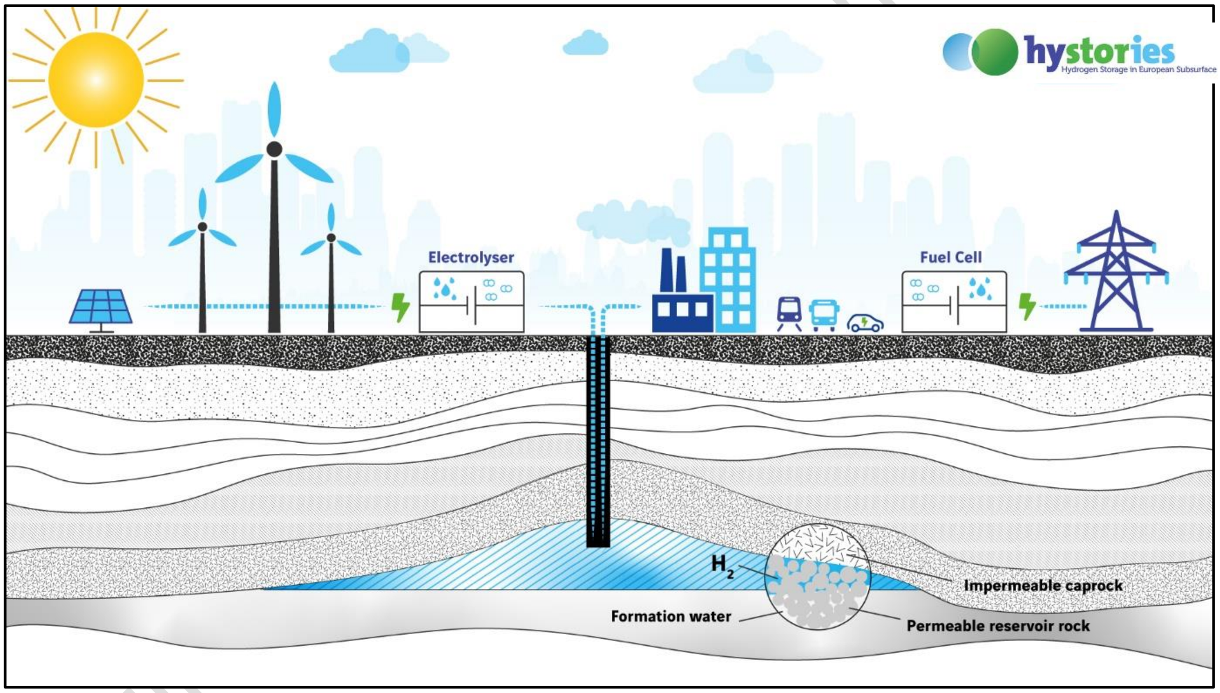

Figure 1: Underground storage of Hydrogen in a porous media (depleted hydrocarbon field, aquifer), providing a balance between green hydrogen production from renewable energy sources and offtakers including industry, residential, mobility or power sectors.

Experience and challenges of underground storage of hydrogen

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

- Two areas worldwide host salt caverns that have been used for storage of pure hydrogen: 3 historical salt caverns have stored hydrogen for approximately 50 years, since it started in 1972 in Europe (at

Teesside, UK), with other facilities located in Texas, US. Public detail on these experiences can be found in SMRI RR 2023-1 (Buzogany et al., 2023)

- Two industrial caverns are being leached in Utah (USA). ACES project (Fernandez et al., 2022)

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

- Six in salt caverns: HyStock (Stouwie, 2024), Hypster (Grange et al., 2023), H2CAST (Kürsel et al., 2024), HyCAVMobil (EWE, 2024), HPC Krummhörn (Panofen, M., Lenze, A., 2023), FrHyGe (FrHyGe, 2024)
- Two in depleted fields: Sun Storage 2030 (RAG, 2023) & EUH2Stars (EUH2Stars, 2024), HyStorage (Uniper, 2024)
- One in an aquifer: BE-HyStore (Fluxys, 2023)
- One in a lined rock cavern: HyBrit (Vattenfall, 2023).

When including both storage of pure hydrogen and of hydrogen blends, 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 caverns, 10 in depleted oil and gas fields, one in an aquifer, and one in a lined rock cavern. From these 29 projects, all of them are in Europe except the two industrial UHS in salt cavern projects under construction or operation in the USA mentioned above, and the Hychico Hydrogen blend storage 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. Since the historical town gas storage, and the existing and mature natural gas storage industry have similar functional and operational principles for design and construction of facilities and wells, it seems sensible to use this experience as a starting point to understand the potential for UHS. Hystories D1.1 'Definition of Selection Criteria for a Hydrogen Storage Site in Depleted Fields or Aquifers' presented favourable and unfavourable characteristics for UHS sites, based on experience from natural gas porous media storage. Despite considerable 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 than natural gas which can be catalysed by anaerobic microorganisms and leads to a potential for geochemical reactions between host rock minerals.
    - Hydrogen causes embrittlement issues for steel materials.
    - 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 similar amount of energy as methane).
- On the spatial and time-frame deployment of the industrial sector:
    - A major infrastructure industry needs to be developed in only a few decades for hydrogen to meet the various decarbonisation targets of individual countries, whereas it took a century for natural gas to develop to its current state.
    - To achieve the adoption of hydrogen to meet energy requirements and decarbonisation targets, a pan-European approach will be beneficial to align energy strategies of individual countries, helping reduce duplication of effort and maximise joint benefits of hydrogen production, storage, transport and use.
    - Planning for deployment of hydrogen infrastructure is being considered at pan-European scale from the beginning, whereas it was developed at regional / national scale for natural gas, and later interconnected.
- Natural gas storage is an established industry, large-scale hydrogen storage is a nascent industry:

  - Drivers for storage capacity requirements (supply and offtake fluctuations) are vastly different (e.g. seasonality of green hydrogen production that isn't the case for natural gas supply).
  - As of today, storage needs in terms of capacity, deliverability, and storage cycles at industrial scale, are hypothetical for hydrogen, 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.

Objectives of the Hystories project

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 natural gas underground storage industry, 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, residual trapping of hydrogen in porous rocks)
- A pan-European overview and ranking of candidate UHS reservoirs or 'traps'.

The knowledge gaps highlighted immediately above are the rationale for the first Hystories strategic objective: to advance technical understanding around these remaining questions for the feasibility and potential scale for implementation of large-scale storage of green hydrogen in depleted fields or aquifers.

Future UHS and transportation networks are infrastructure assets which would reasonably be expected to take a decade to develop and cost billions of Euros. Strategic planning will be key for future social engagement and financial security. Hystories has developed insights to inform decision makers in governments and industry who will take deployment decisions. This is the rationale for the second strategic objective of the Hystories project: to undertake a techno-economic assessment of how the underground storage of renewable hydrogen could facilitate achievement of an EU zero-emissions energy system by 2050.

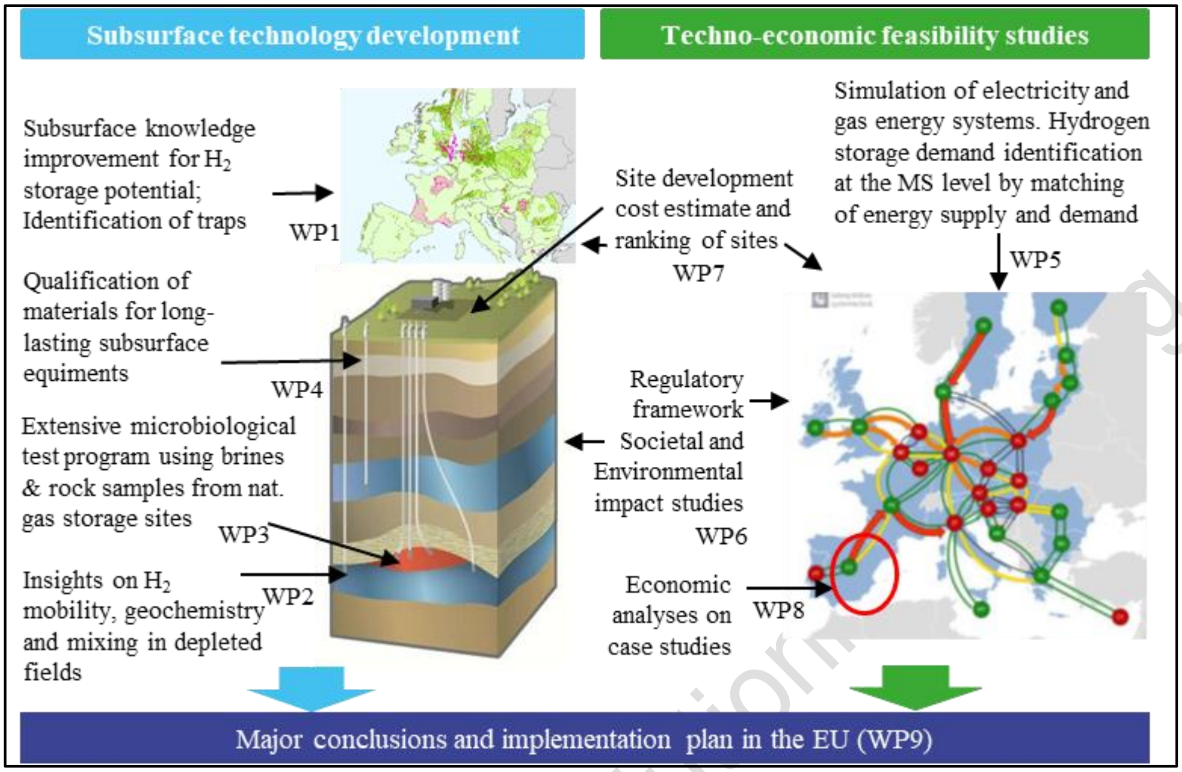

Figure 2: Hystories work programme (WP is workpackage). Left “Subsurface technology development” and right “Techno-economic feasibility studies” columns are the two strategic objectives of the Hystories project.

Hystories main technology developments (WP1-4)

Hystories aimed to identify UHS potential sites in depleted hydrocarbon fields and saline aquifers both onshore and offshore across Europe. Publicly available data were analyzed, building on the work of previous European projects (most notably the results of the CO_2StoP[1] and ESTMAP[2] projects). New data were collated from reputable sources including publications, geological maps, well stratigraphy and geophysical logs. For instance, 26 traps were identified and characterized, onshore and offshore in Italy, as presented in Figure 3.

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[1] https://setis.ec.europa.eu/european-co2-storage-database_en

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

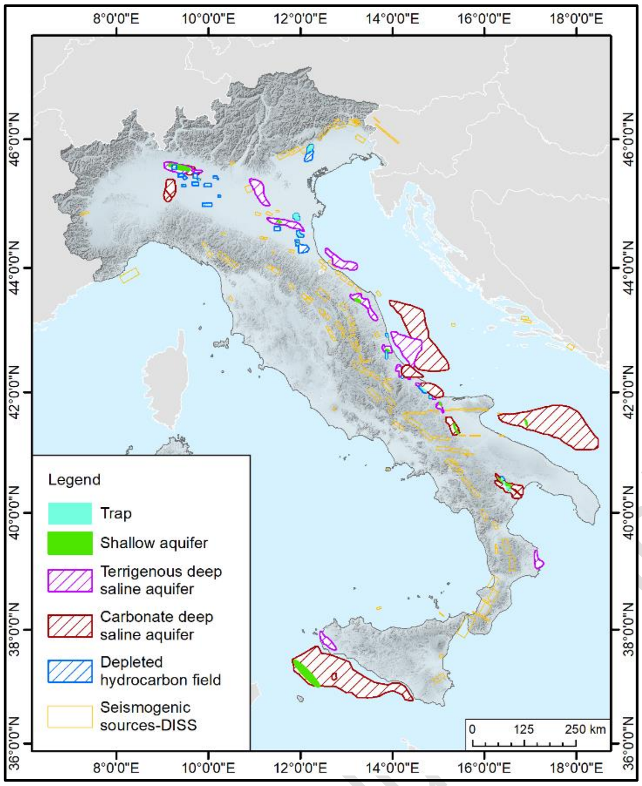
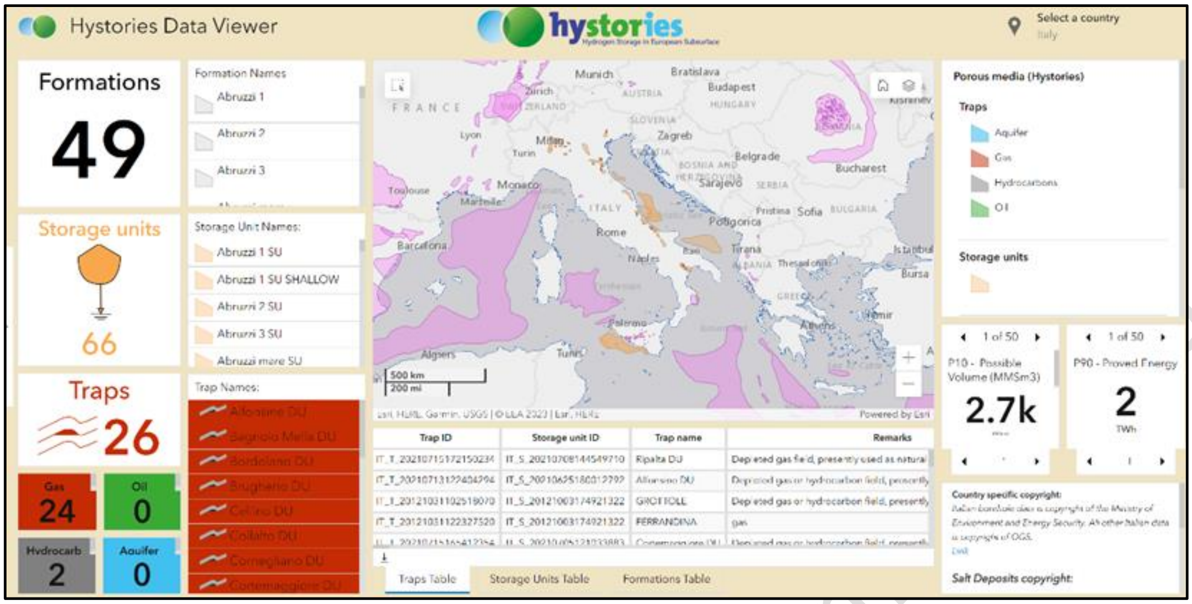


Figure 3. Map of the distribution of the potential UHS site in Italy. Basemap Copyright Esri, TomTom, Garmin, FAO, NOAA, USGS. The hydrocarbon fields locations are derived from a public database available from https://unmig.mite.gov.it/stoccaggio-del-gas-naturale/ (accessed on 12 February 2023) except for the Treviso field which was adapted from Mattera et al., 2023. Aquifer outlines are copyright OGS.

The assessment of potential geological stores was carried out by 17 European geological surveys or research institutes covering 23 individual European countries, as presented in Hystories D1.4 ‘Opportunities in Europe for geological storage of hydrogen in depleted hydrocarbon fields and saline aquifers’. 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.



Trap ID	Storage unit ID	Trap name	Remarks
IT_T_20210715172150234	IT_S_20210708144549710	Ripalta DU	Depleted gas field, presently used as natural
IT_T_20210713122404294	IT_S_20210625180012792	Alfonsine DU	Depleted gas or hydrocarbon field, presently
IT_T_20121031102518070	IT_S_20121003174921322	GROTTOLE	Depleted gas or hydrocarbon field, presently
IT_T_20121031122327520	IT_S_20121003174921322	FERRANDINA	gas

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Figure 4: Public GIS visualization of the European scale porous media database for Italy. Basemap Copyright Esri, HERE, Garmin, USGS | © EEA 2023 | Esri, HERE

Based on the information contained in this database, the Hystories project estimated storage capacity for 800+ porous traps in EU-27 and four neighbouring countries, with 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 '3D multi-realization simulations for fluid flow and mixing issues at European scale') as presented in Figure 5. It was then possible to estimate the possible hydrogen working volume for each country as presented in Figure 6.

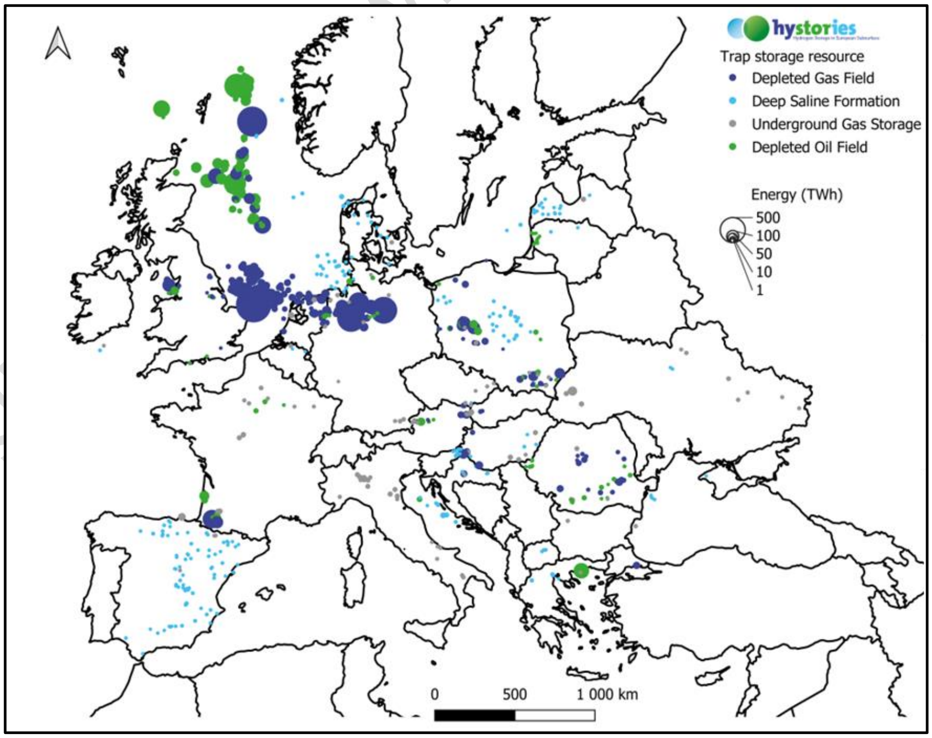


Figure 5: Map of hydrogen working-gas storage resource estimation. From Le Gallo, 2024

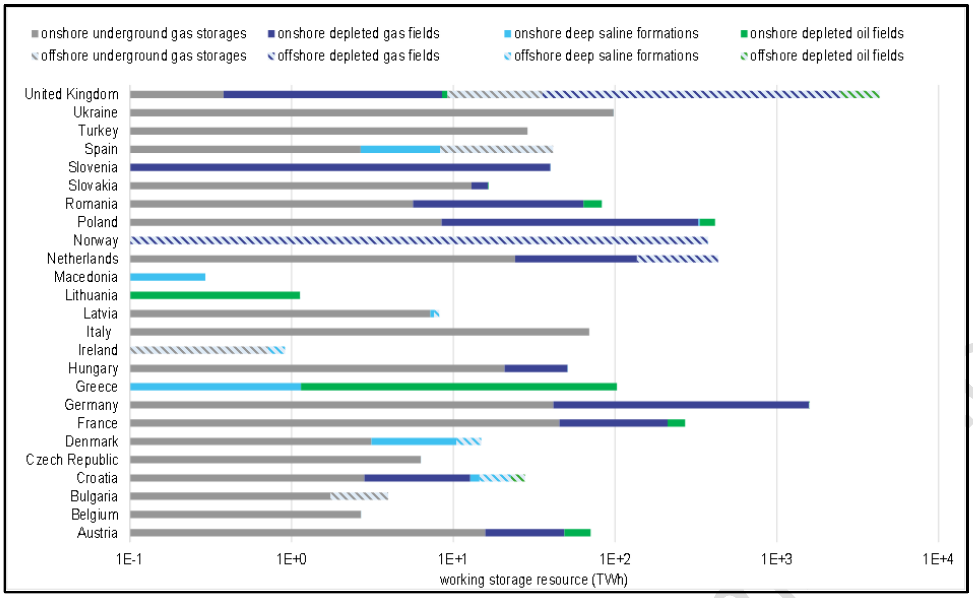


Figure 6: Total hydrogen working gas storage resources for different porous media per country. From Le Gallo, 2024

To assess the potential risks associated with microbial activity in future underground hydrogen storage facilities, downhole samples were obtained from eleven porous media natural gas storage sites in Europe, covering a wide range of conditions relevant to UHS. These waters were analysed, and the microorganisms were characterized as part of WP3. Groups of hydrogen-consuming microorganisms were found in all but one of these formation water samples. Low and high hydrogen pressure reactivity tests were performed to assess the consumption rate of hydrogen, and specific parameters which could impact consumption were identified. 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.

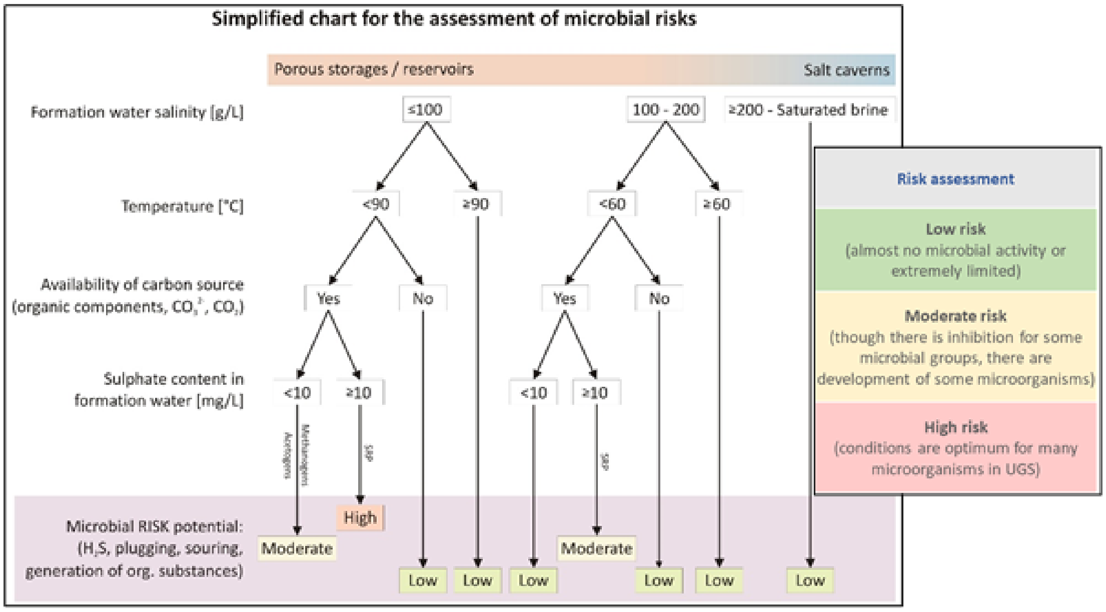
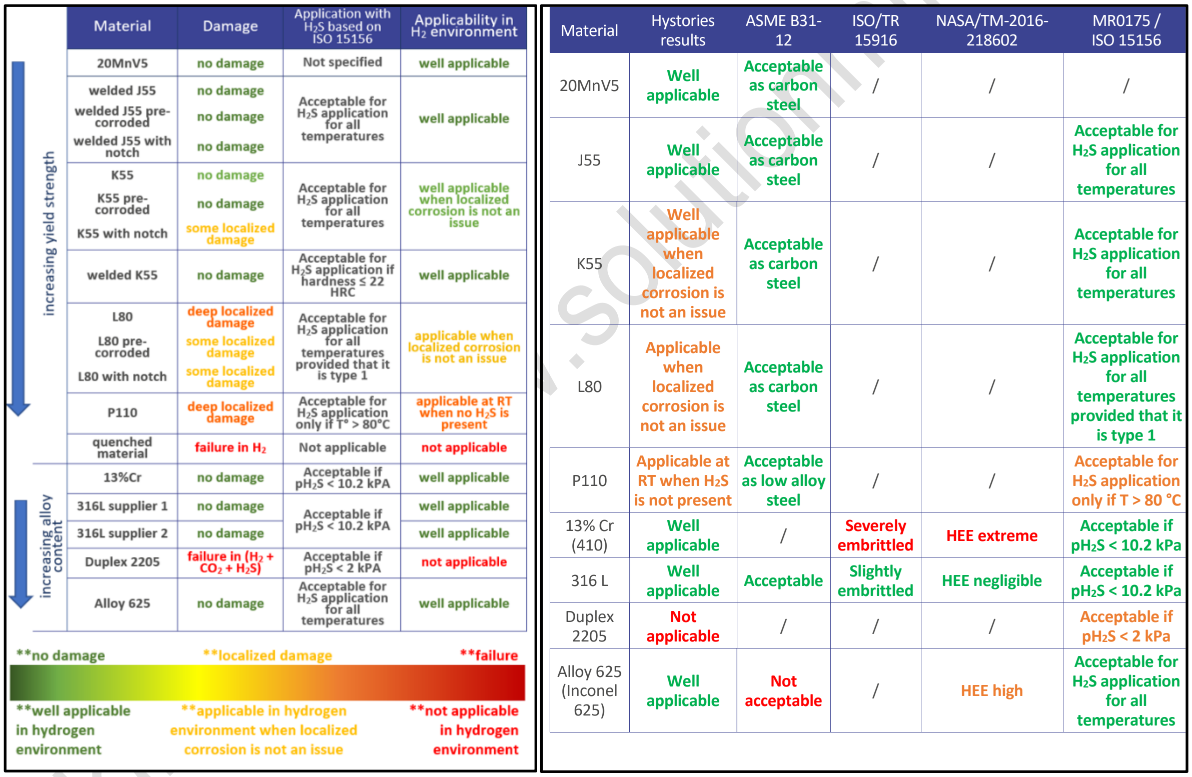


Figure 7: Simplified chart for a risk assessment for UHS based on temperature, salinity, carbon and sulphate availability. From Hystories Deliverable 3.4 'Synthesis of the risks and actions to correct these risks depending on the environment'.

The Hystories project used experimental results and historical industrial town gas experience to **develop geochemical models of the bio-reactivity** in box models, these were then applied at large-scale through 3D modelling to **assess the expected impacts at operational storage scale**. In one specific storage case study, 0-D and 3-D models were developed to predict reaction kinetics during five seasonal cycles of hydrogen injection and withdrawal. This case study indicated that hydrogen consumption was 5 % after the laboratory experiments had run for 70 days. Using 3D reactive modelling, hydrogen consumption at the end of the five seasonal cycles was expected to be 0.06 % using the laboratory-scale reactivity, and **0.004 % using the storage scale reactivity** as presented in Hystories Deliverable D3.3 ‘Modelling of microbial effect on H_2 reactivity in porous media at laboratory and reservoir scales’.

Hystories **tested a dozen grades of well casing steel in a hydrogen rich environment**, under constant or cyclic load conditions, to analyse localized corrosion, damage, hydrogen uptake and permeation, and finally assessed **suitability of these casing steel for storage wells (WP4)**. Based on the results of localized corrosion rates and cracking under constant load testing, an overview of the suitability of these investigated materials was presented, as shown on Figure 8. It should be noted that results observed during Hystories laboratory tests sometimes differ from the assessment found in other public literature, notably due to relatively severe H_2S conditions used in Hystories



	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 welded J55 pre-corroded welded J55 with notch	no damage no damage no damage	Acceptable for H_2S application for all temperatures	well applicable
	K55 K55 pre-corroded K55 with notch	no damage no damage some localized damage	Acceptable for H_2S application for all temperatures	well applicable when localized corrosion is not an issue
	welded K55	no damage	Acceptable for H_2S application if hardness ≤ 22 HRC	well applicable
	L80 L80 pre-corroded L80 with notch	deep localized damage some localized damage some localized damage	Acceptable for H_2S application for all temperatures provided that it is type 1	applicable when localized corrosion is not an issue
	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: Suitability of steel grades tested during the Hystories project. Results of Constant Load Tests (left, from D4.6 ‘Summary report on all investigated steels’) and comparison with suitability recommendations found in published literature (right, from D4.7 ‘Synthesis of the Materials and Corrosion Investigations’)

Major socio-economic findings from the Hystories project (WP5-8)

The regulation readiness level for UHS was assessed based on surveys of stakeholders which were launched in 2021. The survey results indicated that regulations were developed or under development for six of the 17 European countries reviewed (Table 1, WP6). Detailed procedures were summarized for France, Germany, Poland and Spain. (Hystories Deliverable D6.1 'Assessment of the Regulatory Framework').

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

Current legal framework	Country
Legislation in force for 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 products, not specific to UHS [3] Long-term operational experience for cavern storage of hydrogen for industrial use [4] UHS mentioned in national strategies	

Assessment covering seven 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 9):

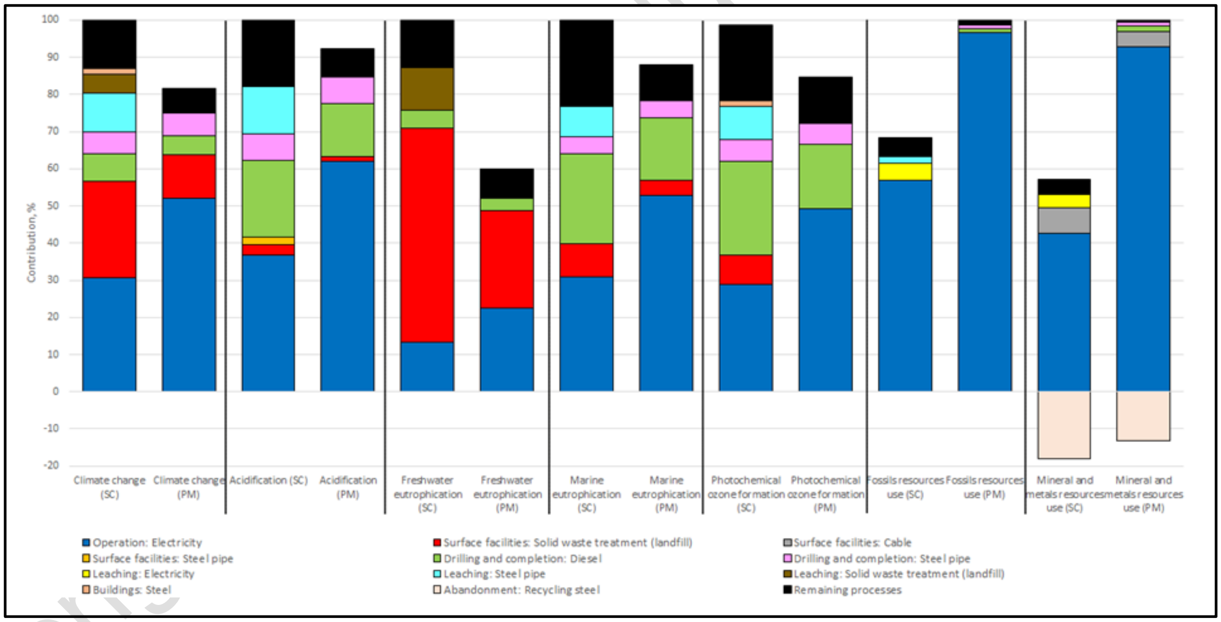


Figure 9: Contributions of main processes of salt cavern (SC) and porous media (PM) by impact category. From Hystories D6.3 'Report on the environmental impact of the underground H2 storage'

A Social Impact Study around perceptions of UHS was undertaken. In three countries, members of the public were invited to participate in a survey to collate their views. Survey results suggested that the public were concerned about UHS development in their local area (sometimes known as "Not in My Backyard" phenomenon). A second survey was undertaken where UGS project stakeholders were invited to provide their views on the impact of social engagement, this survey found that construction of two storage projects had been stopped or delayed by public pressure (Hystories D6.4 'Social impact of the underground H_2

storage'). However, it should be noted that the number of projects in which these UGS project stakeholders were involved is unquantified by the survey, and therefore it is difficult to ascertain what percentage these two cancelled/delayed projects represent in terms of overall project development. Follow-up interviews with the UGS project developers clearly indicated that dialogue with local community to raise awareness and address concerns is key for successful implementation.

A comprehensive energy system modelling was performed for EU27+UK in WP5. In total, four scenarios were developed (see Hystories D5.1 'Scenario definition for modelling of the European energy system') and analysed considering (a) different H_2 production pathways (domestic production vs. imports from non-EU regions) and (b) different H_2 storage technologies (salt caverns, storage in porous media, and 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 needed in the short-term (by 2030) to meet demands of 20 - 40 TWh_{H2} (or 7 – 14 billion m³)**, including mainly salt caverns but also porous media storage. **In the long term (after 2030), the required storage volume capacities in the scenarios grow substantially to more than (300 TWh_{H2} or 100 billion m³ in 2050) with an equal split between salt cavern and porous media capacity.** The capacities strongly depend on the overall hydrogen demand (1,700-1,900 TWh/a expected in 2050) from various end-use sectors (industry, mobility and heating accounting for up to 90 % of total demand) and from the power sector (i.e. re-electrification). Although potential storage capacities for pure hydrogen might be lower on a TWh-basis in comparison to today's conventional natural gas (ca. 1,000 TWh_{CH4}), the need for geological reservoirs is expected to be similar owing to the lower volumetric energy density of hydrogen and responding to fluctuating supply-demand profiles. 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 storage projects (up to 10-12 years incl. planning), there is an urgent need to anticipate storage requirements and to develop and build sufficient capacities in time.

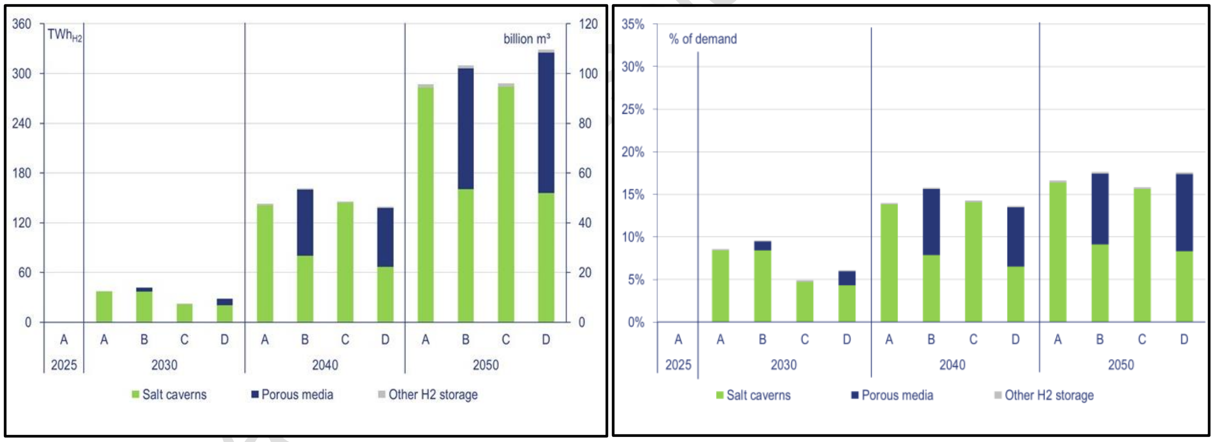
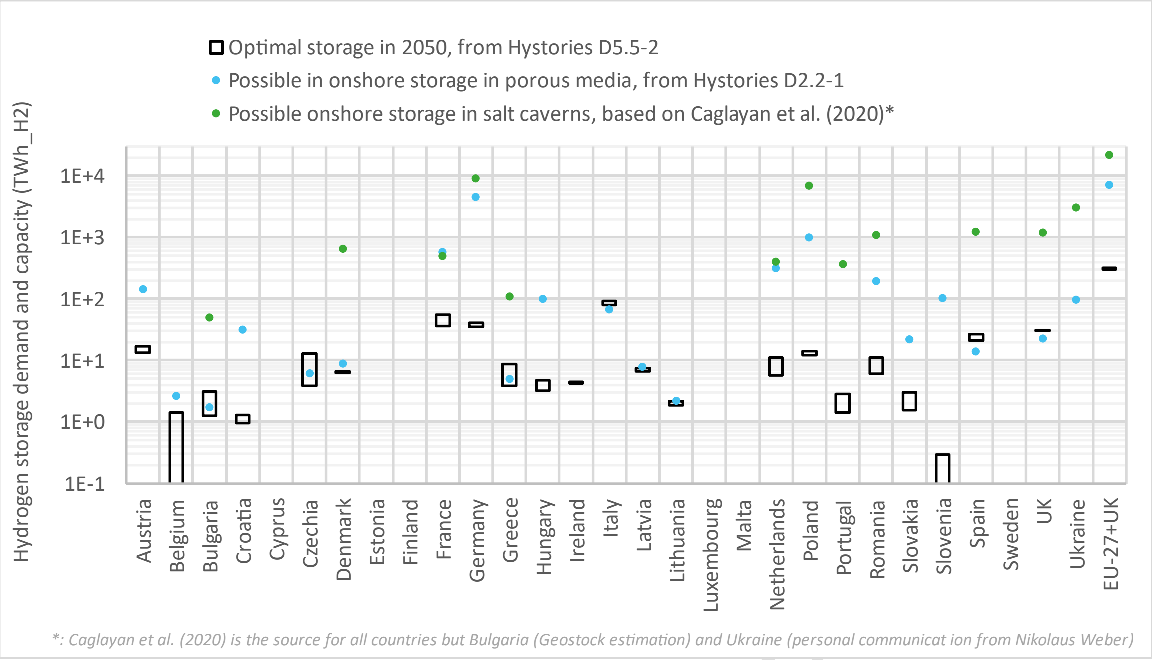


Figure 10: Optimal storage volume capacity in absolute values (left) and as percentage of overall hydrogen demand (right) in EU-27 & UK (Source: Hystories D5.5 'Major results of techno-economic assessment of future scenarios for deployment of underground renewable hydrogen storages')

These **storage demand figures are typically 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 (literature search result)** in EU-27+UK (Figure 11). This suggests that geology may not represent a major barrier to achieving UHS ambitions in the mid- long-term



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

Figure 11: 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 Hystories D7.3 'Ranking and selection of geological stores'

To rapidly develop the needed storage capacity, **the possible UHS sites in Europe need to be ranked**. This activity which was performed in WP7. The cost for an underground storage is dependent on site-specific characteristics and on the cycle frequencies and pressure ranges under which the storage will operate. A typical design of an integrated UHS, including surface facilities, was developed for three capacity/withdrawal flowrate scenarios (Hystories D7.1 'Conceptual design of salt cavern and porous media underground storage site') and used to develop a bottom-up cost model with well-defined boundary limits (Hystories D7.2 'Life Cycle Cost Assessment of an underground storage site'). This model is parametric, hydrogen-specific and allows a full lifecycle cost assessment, including development, construction, commissioning & start-up, operation & maintenance, and abandonment. This model was applied for the fast and seasonal cycles identified as priority by energy modelling undertaken during the Hystories project (WP5), and applied to the identified 500+ onshore 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. Fast cycle consists of a full unloading of the storage in 18 days.

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 $\text{LCOH}_{\text{Storage}}$, part of the Levelized Cost Of Hydrogen[3], 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.

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[3] $\text{LCOH} = \text{LCOH}_{\text{production}} + \text{LCOH}_{\text{transport}} + \text{LCOH}_{\text{storage}} + \text{LCOH}_{\text{other}}$. Cf. for instance D5.5-2

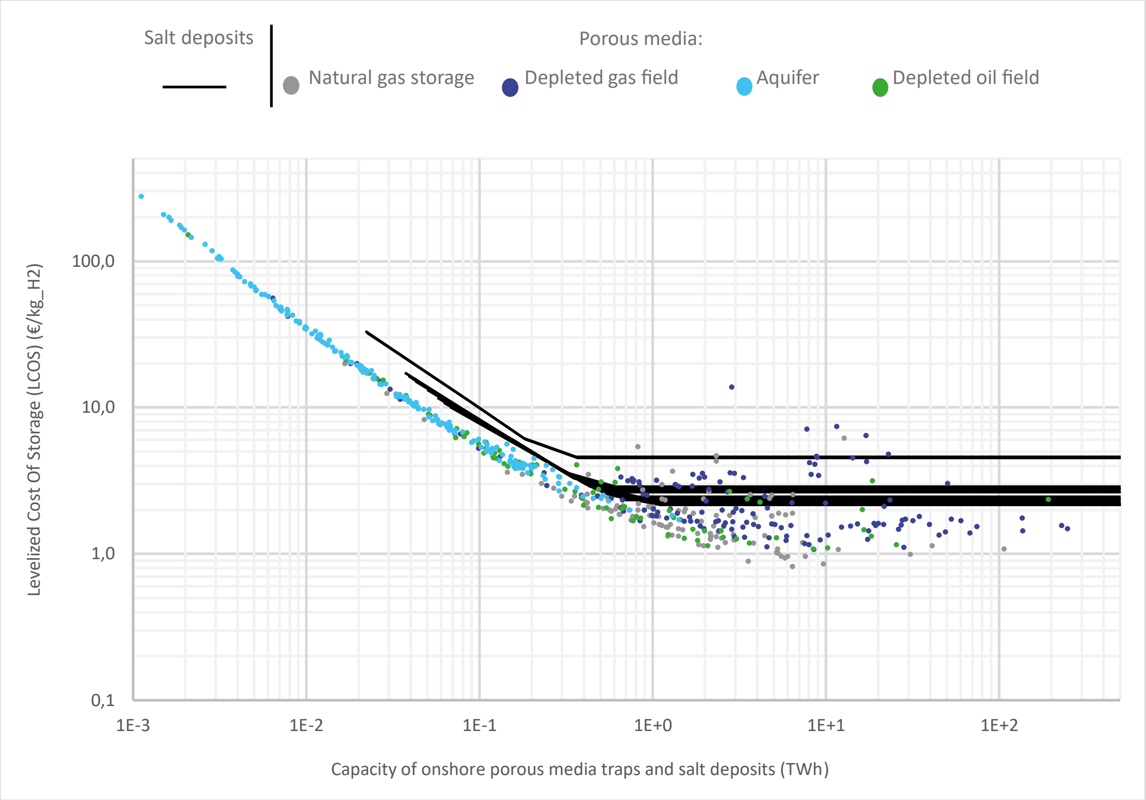

Figure 12: LCOS for onshore porous media and salt caverns in EU-27+UK+Ukraine, seasonal cycle, per capacity. For porous media (dots indicate the maximum capacity of the trap) and for salt caverns (size to be chosen by design on the solid line). From D7.3-1

A suitability mark reflecting relatively higher readiness and lower technical risk, was estimated for porous media traps and salt caverns. It resulted in **higher suitability marks for salt caverns, followed by existing natural gas storage sites and depleted gas fields. This indicated that salt caverns, followed by existing natural gas storage sites in porous media and then depleted gas fields are the preferred options for UHS based on the current state of knowledge.**

Case studies for specific UHS sites in France, Germany, Italy, Poland and Spain in WP8 enabled a more detailed review of the implementation of UHS projects, notably by assessing economic opportunities under different regulatory and economic framework conditions and identifying the most relevant business case-related factors. However, detailed studies will be needed for individual sites to fully account for the characteristics and situation of each potential storage project.

High level conclusions on UHS maturity and insights for UHS deployment in Europe

The high-level conclusions of the Hystories project in terms of the maturity of UHS are as follows:

- Hydrogen Storage in salt caverns is seen as technically mature, owing mainly to the 50+ years of industrial experience and to the low risk of microbiological activity. However, technical development is a continuous process and is desirable for several components of the technology[4].

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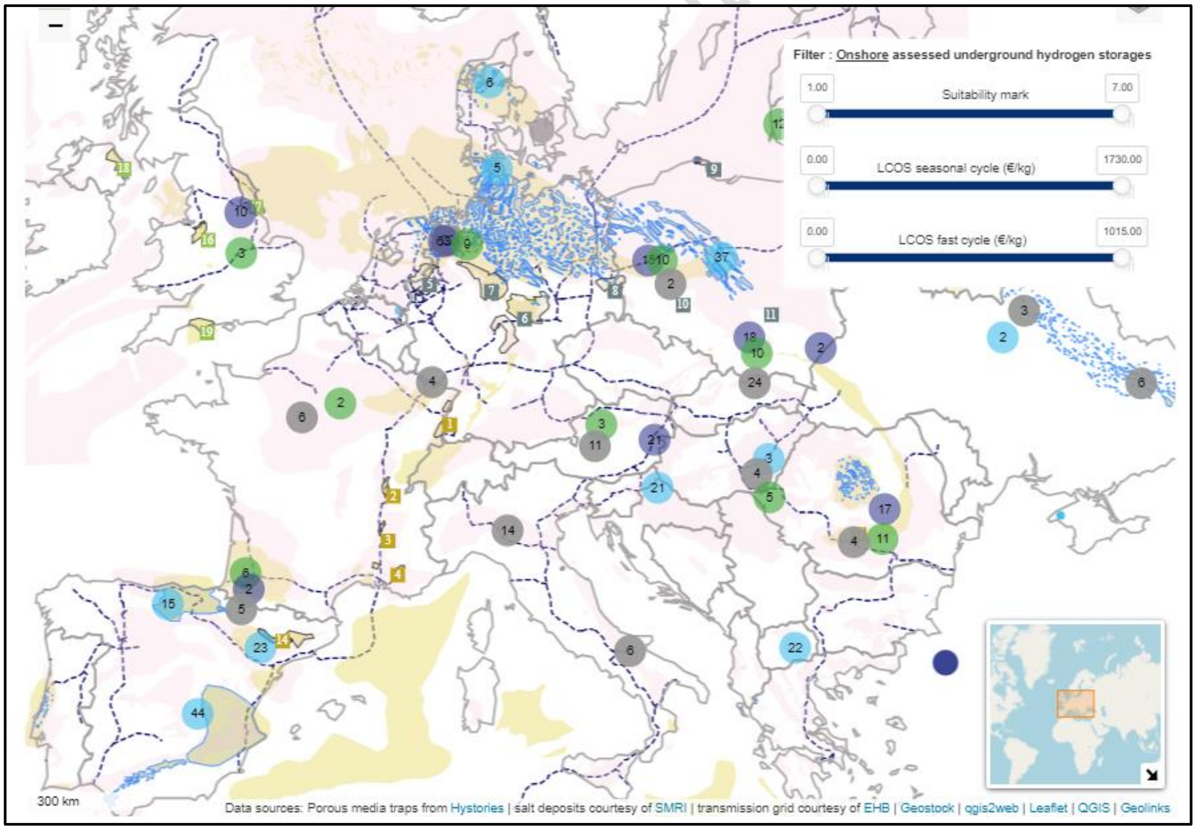
[4] Salt cavern technical development were not the focus of Hystories. SMRI report RR2023-1, by Buzogany et al. 2023, provides a clear industrial view on the remaining knowledge gaps.

- No obvious technical showstopper is foreseen for hydrogen storage in depleted gas fields or aquifers. However, the purity upon withdrawal (owing 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 for H_2 storage is forecasted to increase strongly after 2030 owing to an expected significant demand for H_2 and substantial share of intermittent power use in hydrogen generation. The value of UHS of green 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 such as production overcapacities. This economic interest calls for hydrogen infrastructures to be operational as early 2030, which would require immediate investment decisions. However, the business frameworks that would encourage industrial projects to develop are not yet mature in Europe. Solving this “chicken and egg” barrier to large-scale implementation problem is one of the most significant issues facing UHS.

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

These results have been used to derive the Levelized Cost Of Storage (LCOS) and Suitability Mark presented in Hystories D7.3. In addition to these scoring parameters, assessing the opportunity for UHS development also requires consideration of location and proximity to foreseen hydrogen pipelines to reduce cost. The Hystories project 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 onshore storage solutions (aquifer, depleted oil and gas field, salt cavern) (Figure 13).



Filter : Onshore assessed underground hydrogen storages

Suitability mark: 1.00 – 7.00

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

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

Data sources: Porous media traps from Hystories | salt deposits courtesy of SMRI | transmission grid courtesy of EHB | Geostock | qgis2web | Leaflet | QGIS | Geolinks

Figure 13: Hydrogen storage opportunity map, from www.hystories.eu/map

Recommended actions

The following sections present the overarching recommendations that are considered key to enabling pan-European UHS deployment by the Hystories project.

Recommendation for continuous geological data collection, analysis, interpretation and publication

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. Data may be held confidential or may not have been collected in the regions of interest. 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. Depleted gas fields and gas storage sites have the proven ability to store buoyant fluids, and usually have a wealth of site-specific data including reservoir models which can be used to consider the suitability of a geological store for hydrogen. Saline aquifers may offer significant capacity and often have the advantage of fewer legacy wells to consider in terms of risk of migration routes for buoyant fluids. However, many saline aquifers have not been considered economically interesting to date, therefore usually fewer data are available to assess potential traps and collection of new data will be required to provide assurance on security of storage. In addition, the ability of a trap in a saline aquifer to contain buoyant fluids is unproven until storage has taken place. The Hystories database is far from including all existing potential traps in the European subsurface. Regarding the number of depleted fields, there is a need for public data release in some countries and should be considered a conservative appraisal of storage opportunities. The EU Net Zero Industry Act (NZIA) is expected to result in the release of more data on depleted hydrocarbon fields which will require analysis and interpretation. How these data are shared is also important since a harmonised approach and making more data publicly available will increase knowledge and make it easier to generate useful products following data analysis and interpretation.

Recommended actions:

- Build on the Hystories database to further advance this first pan-European opportunity map focused on hydrogen storage.
- Develop harmonised European guidance that enables a reference database that has to be improved whenever additional geological data is publicly released from new or historical exploration (particularly under the NZIA).
- Additional funding to be made available for analysis and interpretation to complete the database for available traps, and to add new formations, units and traps as newly released data becomes available.
- Expand the geographical scope of the Hystories database.
- Include not only the SMRI salt deposits (which can be seen as analogous to the “formation” level in the Hystories database which highlights areas worth investigation since suitable geology is present), but also undertake assessment to highlight areas where storage cavern is *a priori* technically feasible (which would be closer to the porous media “traps” level in the Hystories database).
- Expand the database scope by including where the geology may be suitable for the building of lined rock caverns.

Recommendation for pilot projects in porous media

As presented in Section 2, as of today, there are two ongoing industrial H_2 caverns being developed (in the USA), and 10 storage pilot projects recently commissioned or under construction in Europe, among which six are in salt caverns, two in depleted gas fields, one in an aquifer, and one in a lined rock cavern. For 2023, the IEA Clean Technology guide[5] assessed the Technology Readiness Level for pure hydrogen

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[5] https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide on 01/08/2023

storage in depleted gas fields and aquifers as significantly lower than for salt caverns (Technology Readiness Levels of respectively 5, 3 and 9-10). Demonstrating the feasibility of hydrogen storage in depleted gas fields and aquifers is now of great interest, as porous media storage can offer a highly suitable option to store large quantities of hydrogen. Research into the impact on gas quality of mixing and microbial conversion of hydrogen are of particular interest and would require gas quality observations at pilot or industrial scale sites over longer time periods.

Recommended actions:

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

Business frameworks and regulation in Europe

Even though UHS in salt caverns is seen as technically mature, there are only isolated pilot scale green hydrogen storage developments in Europe today, whereas there are two industrial-scale hydrogen caverns being leached without a preceding pilot project in the USA. The lack of viable business case for project developers in Europe is likely part of the explanation. Pilot projects can enable a rapid ramp-up of available UHS capacity (potentially up to 20-40 TWh by 2030 according to modelling undertaken in the Hystories project) in line with the development of a trans-European hydrogen transport infrastructure by 2030.

Recommended actions:

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

Recommendations 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.

Recommended actions:

- Enhance publicly available UHS cost estimations, notably:
  - Further efforts are needed to design and generate cost estimates for the gas treatment process for UHS in porous reservoirs (which notably depends on future gas grid injection specifications)
  - Include feedback from the pilot projects and emerging industrial UHS experience

  - Publish and collate cost models for very small or large, porous media or salt cavern projects.
- Publish cost estimations for converting existing assets (e.g. natural gas storage sites, existing salt caverns) and of reuse (e.g. depleted gas fields).
- Undertake holistic review to assess criticality of UHS from a pan-European and Member state perspective, considering *inter alia* security of energy supply (e.g. REPower-EU and national considerations), climate targets, and role for Member States in successful ramp up and integration of intermittent renewable energies. Account for externalities such as supply disturbances, geopolitical developments, and global hydrogen market developments.
- Refine mapping of potential pathways for development of a hydrogen economy to capture local and regional factors, potential hydrogen 'valleys', early deployment opportunities, and grid limitations and congestions.

Recommendations for actions to promote embeddedness for UHS in a sustainable future for Europe

As found by (IEA, 2023):, achieving successful deployment of UHS hinges on reaching a commendable level of societal embeddedness. To foster this acceptance, proactive steps must be taken. This entails transparently sharing information, particularly regarding pilot projects, to demystify the technology and build trust. A national conversation around the need for UHS and hydrogen to meet climate targets and energy needs is required to establish a national understanding for the role and need for UHS. This would then be followed by more local engagement around specific project development, which would be assisted by this improved background understanding at national level. The active engagement of stakeholders and the public in decision-making processes is vital to enable implementation of new technologies. 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. Conducting meaningful public consultations with local communities holds paramount importance for project development. These consultations effectively address the "not in my backyard" phenomenon, fostering mutual understanding and collaboration. The study conducted within the Hystories project underscored the relatively low existing understanding amongst the general public for hydrogen technologies which lags behind other established sustainable alternatives. Thus, actively disseminating information and insights regarding the role for hydrogen, and technology development is pivotal for bridging this gap, hopefully engendering broader support and ushering in a sustainable energy future.

Recommended actions:

- Sharing information on UHS and results from pilot projects
- Involvement of stakeholders/public in national conversation around need for hydrogen and UHS
- Intensify educational campaigns on sustainable energy sources, storage technologies, and climate change to elevate 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 transparently share progress
- Conduct public consultations fostering local cooperation around specific projects at early stages of facility planning and development
- Develop localized case studies showcasing successful UHS integration, bolstering confidence in its viability.

Recommendations for standardisation of well equipment

Standards are available for the selection of suitable grades of steel for hydrogen for surface facilities or pipeline systems. Technical standards are not yet widely agreed for the subsurface aspects of hydrogen storage. Based on related industrial experiences and standards, and on recent H_2-specific research results (including Hystories), it can be concluded that suitable materials are available. A flowchart to select the most suitable material was proposed by the Hystories project, based on environment-specific conditions. However, this mostly focuses on the casing itself, and there is not yet a recognised (e.g. API) standard.

Recommended actions:

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

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