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

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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.

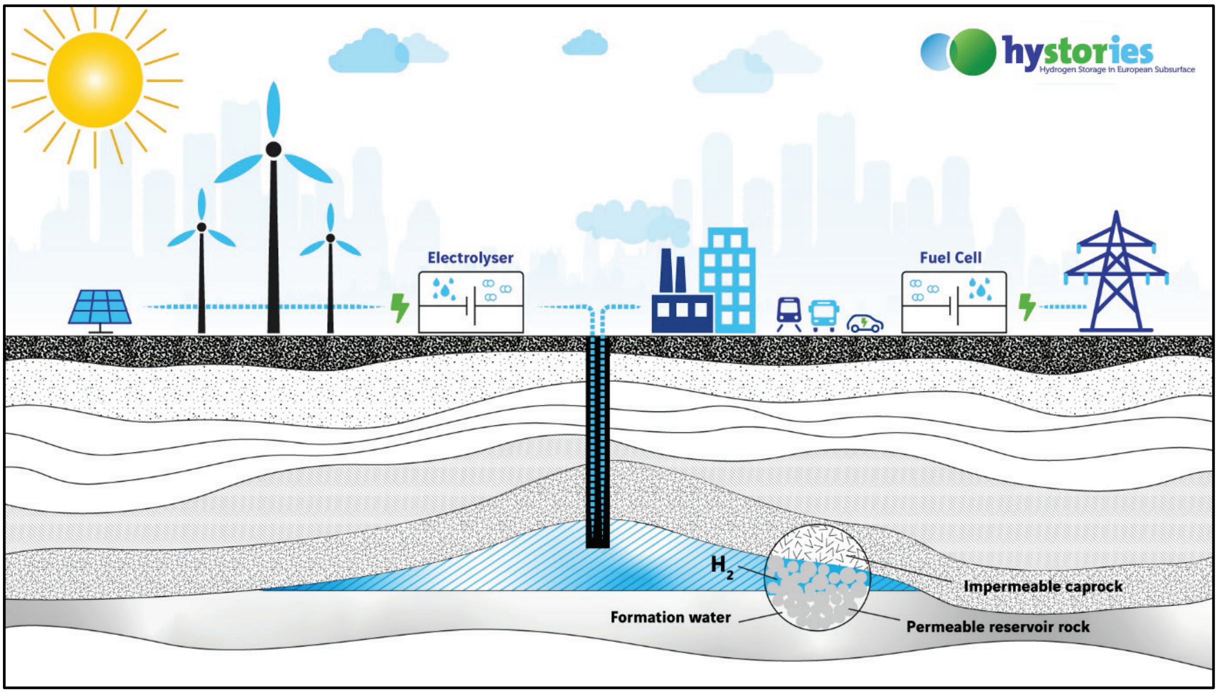

Figure 1: Underground storage of Hydrogen in a porous media (depleted field, aquifer), providing a balance between green Hydrogen production from renewable energy sources and offtakers including industry, residential, mobility or power sectors.

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.

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[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:

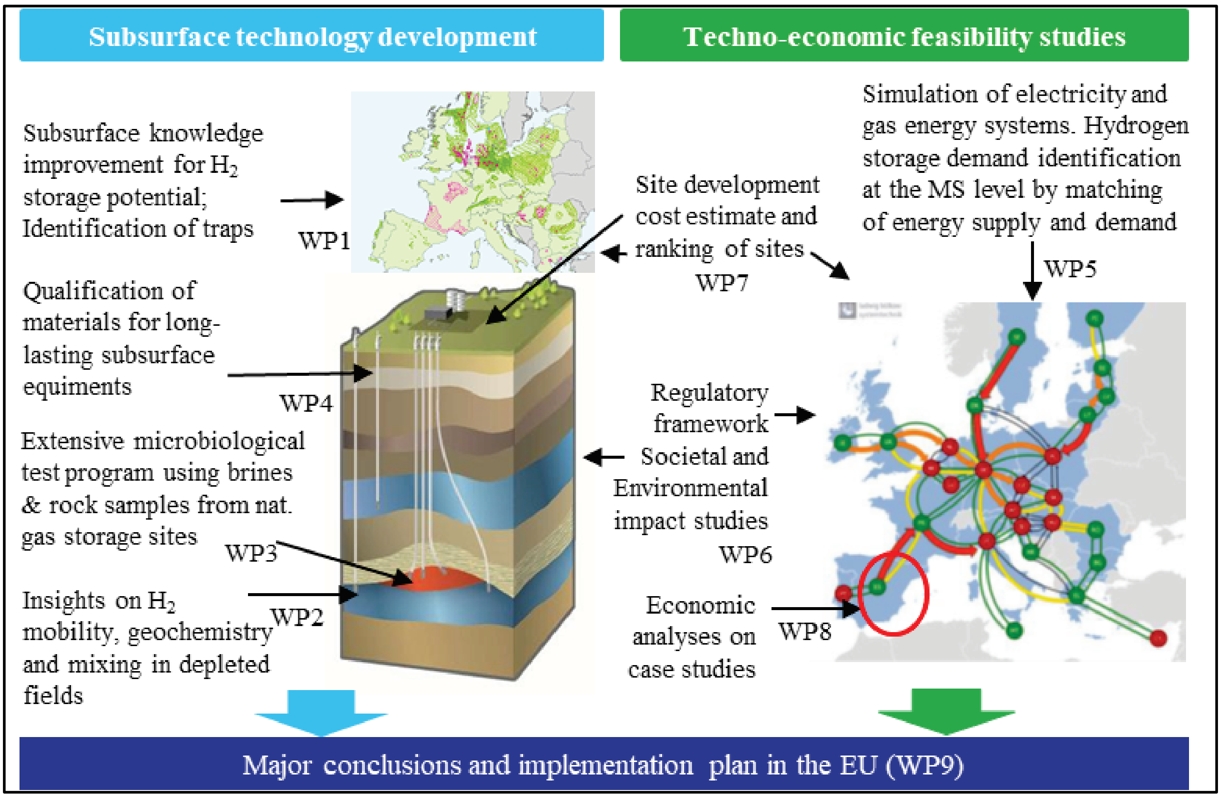

Figure 2: Hystories work program

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.

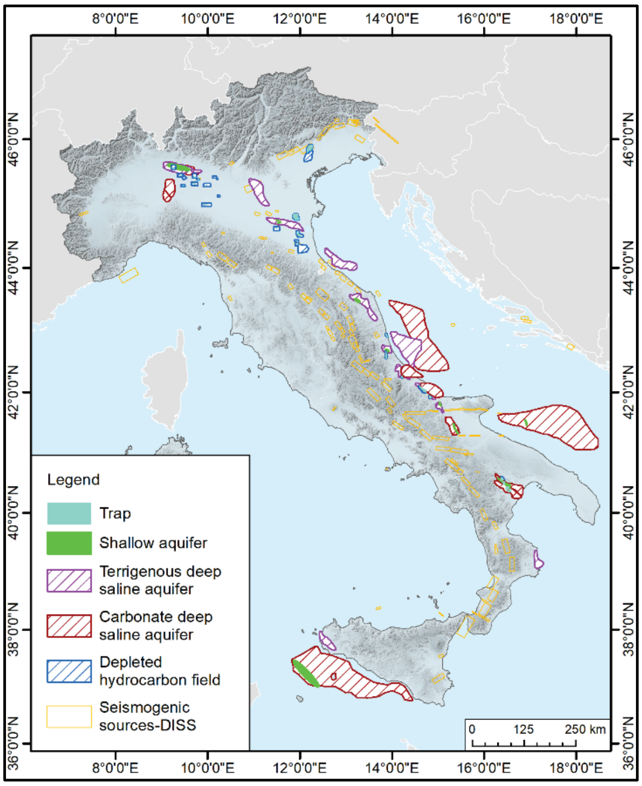

Figure 3. Map of the distribution of the potential UHS site in Italy (Modified from Barison et al., 2023[6])

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

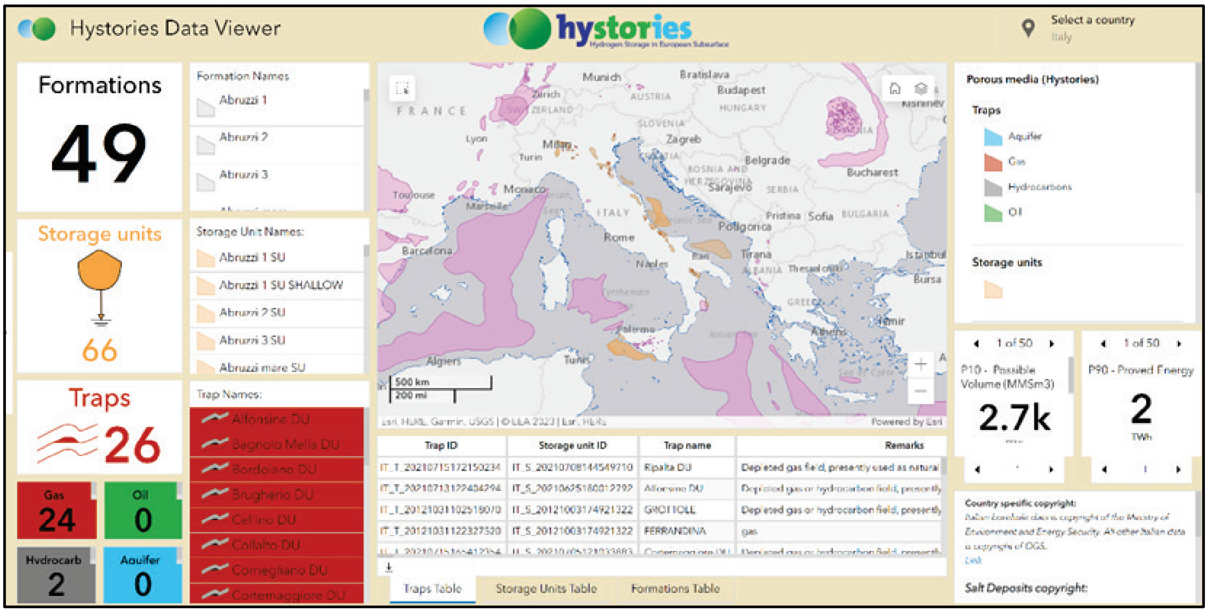

Figure 4: Public GIS visualization of the European scale porous media database for Italy

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.

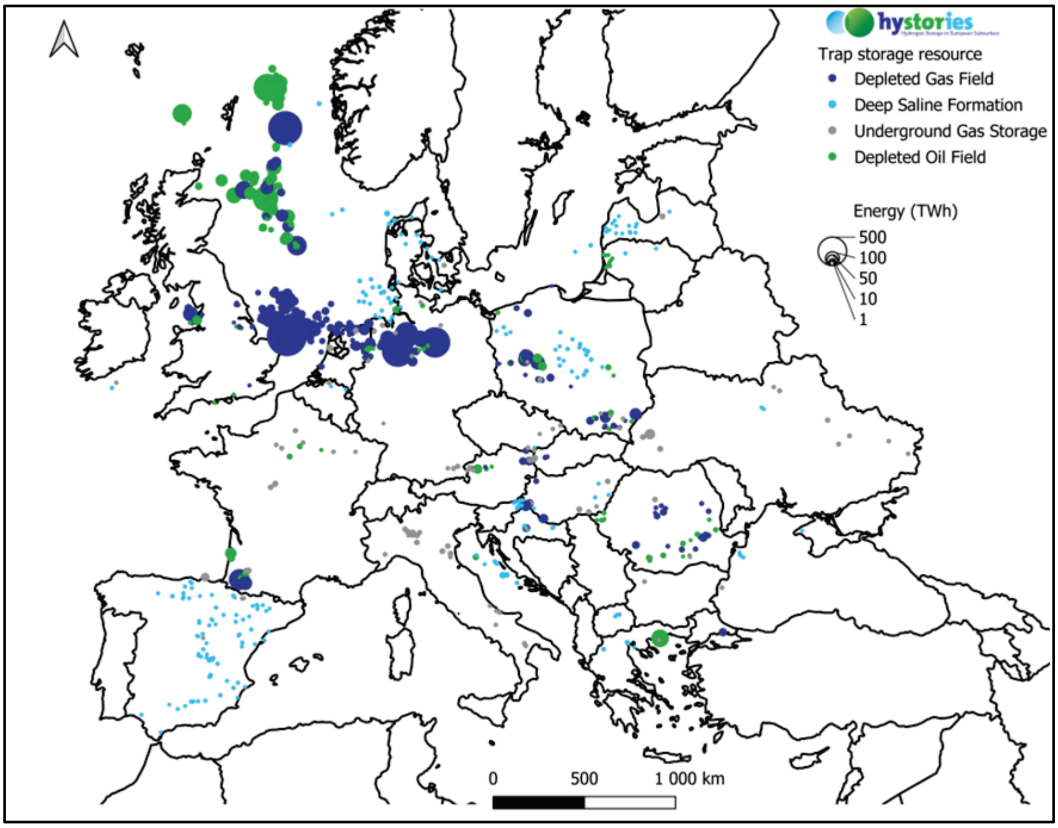

Figure 5: Map hydrogen working storage resource estimation

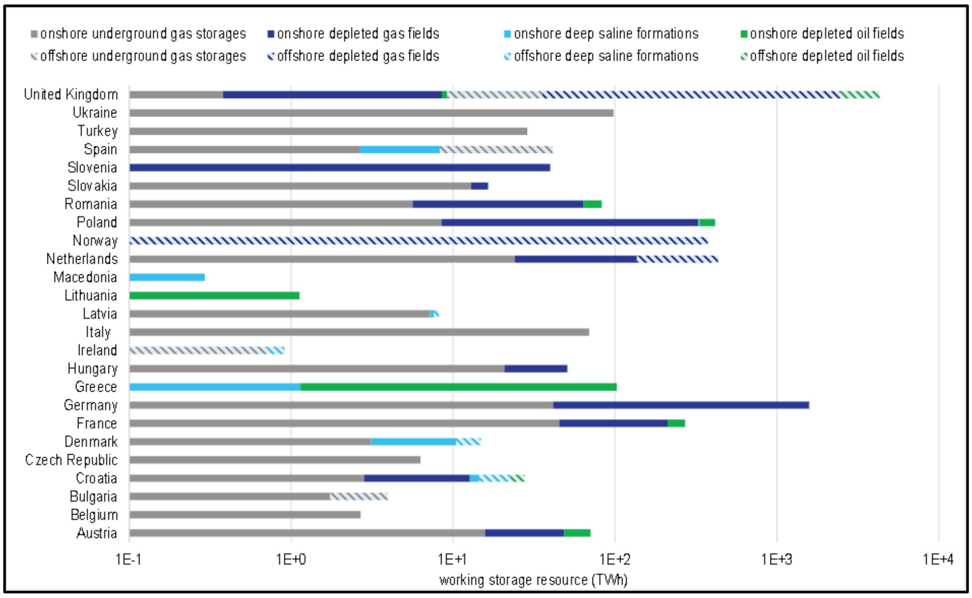

Figure 6: Total hydrogen working storage resources for the different porous media per country

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.

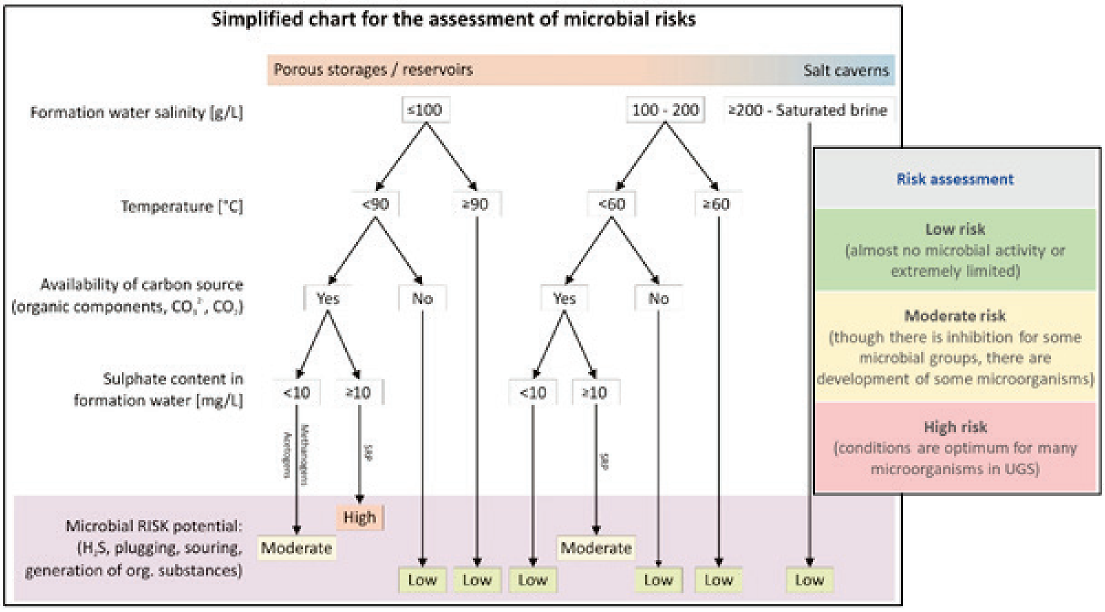

Figure 7: Simplified chart for a risk assessment for UGS based on temperature, salinity, carbon and sulphate availability. From D3.4

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:

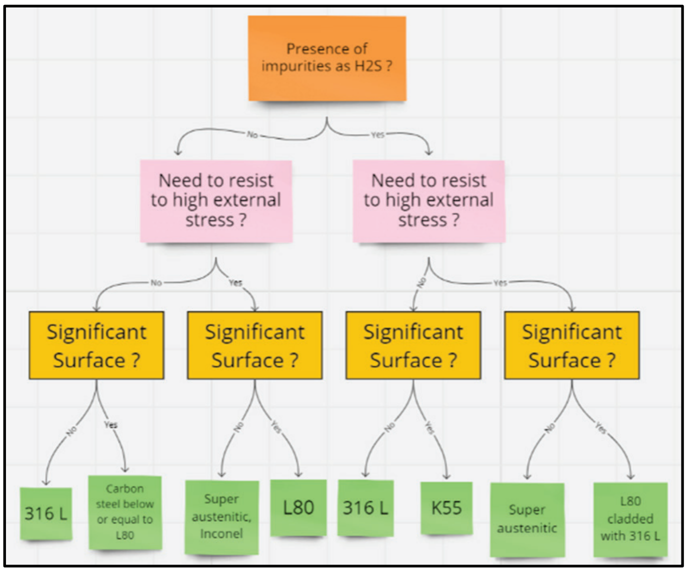

Figure 9: Proposed material selection flowchart for wells in hydrogen environment (gas). This list of materials is not exhaustive and other alternatives could be proposed. From D4.7

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):

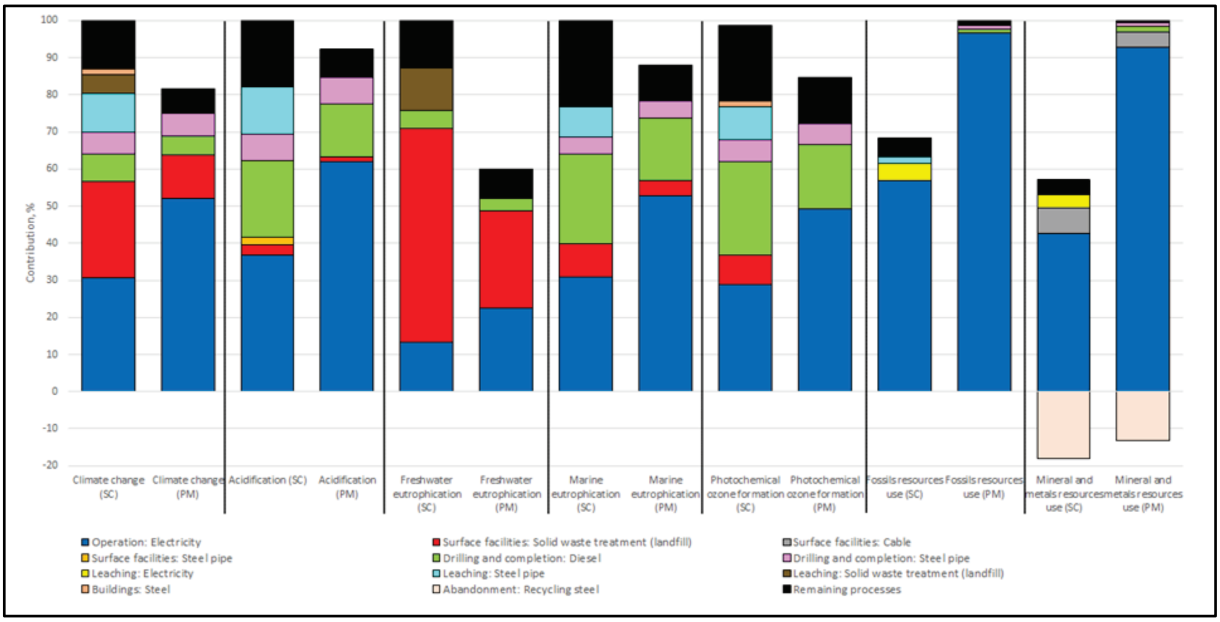

Figure 10: Contributions of main processes of salt cavern (SC) and porous media (PM) by impact category. From D6.3

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.

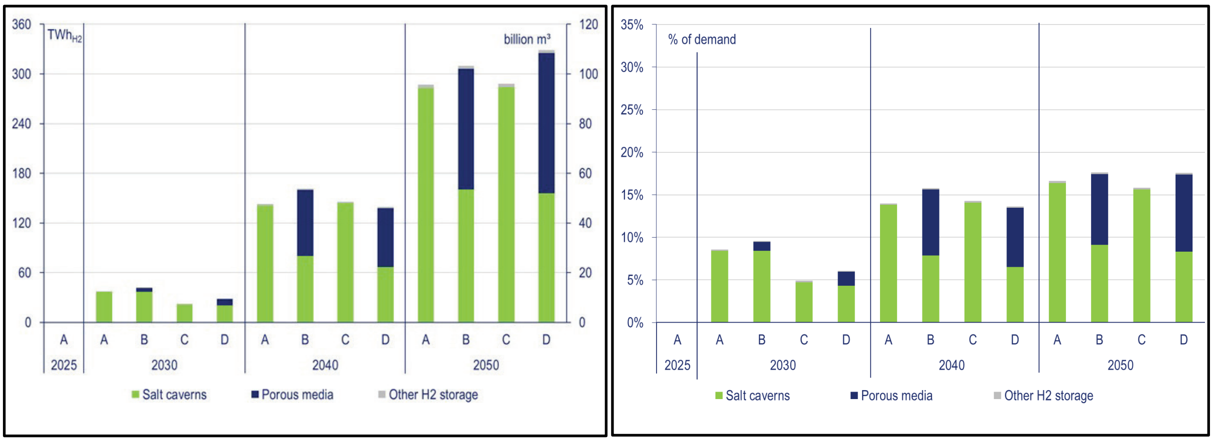

Figure 11: Optimal storage volume capacity in absolute values (left) and as percentage of overall hydrogen demand (right) in EU-27 & UK (Source: D5.5-2)

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):

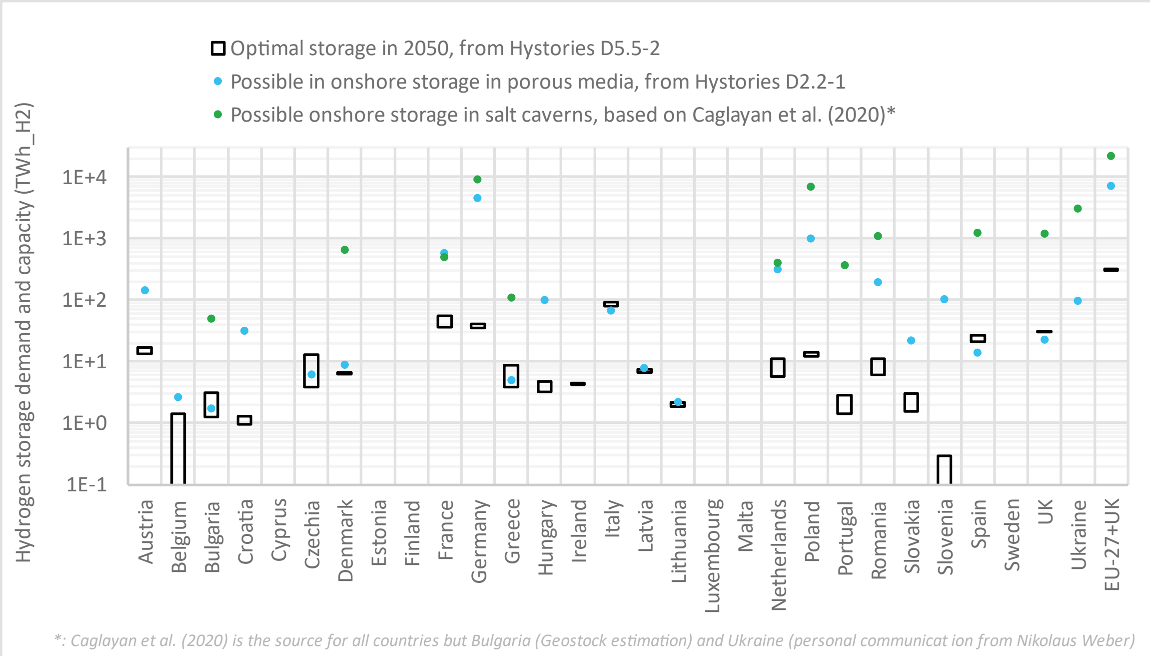

Figure 12: Optimal storage capacity in EU-27+UK+Ukraine in 2050 (scenarios B and D of WP5) and technically possible onshore storage capacity in Porous Media and Salt caverns. From D7.3-1

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

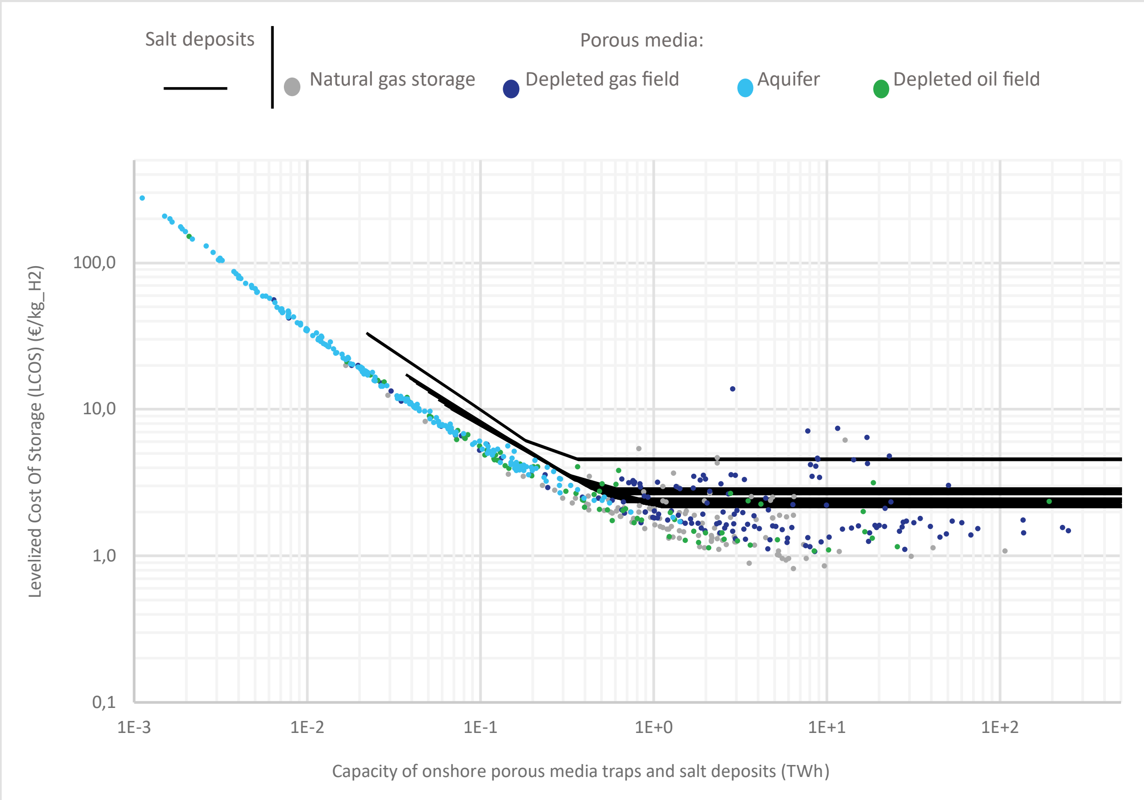

Figure 13: LCOS for onshore porous media and salt caverns in EU-27+UK+Ukraine, seasonal cycle, per capacity. For porous media (dots indicate the maximum capacity of the trap) and for salt caverns (size to be chosen by design on the solid line). From D7.3-1

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.

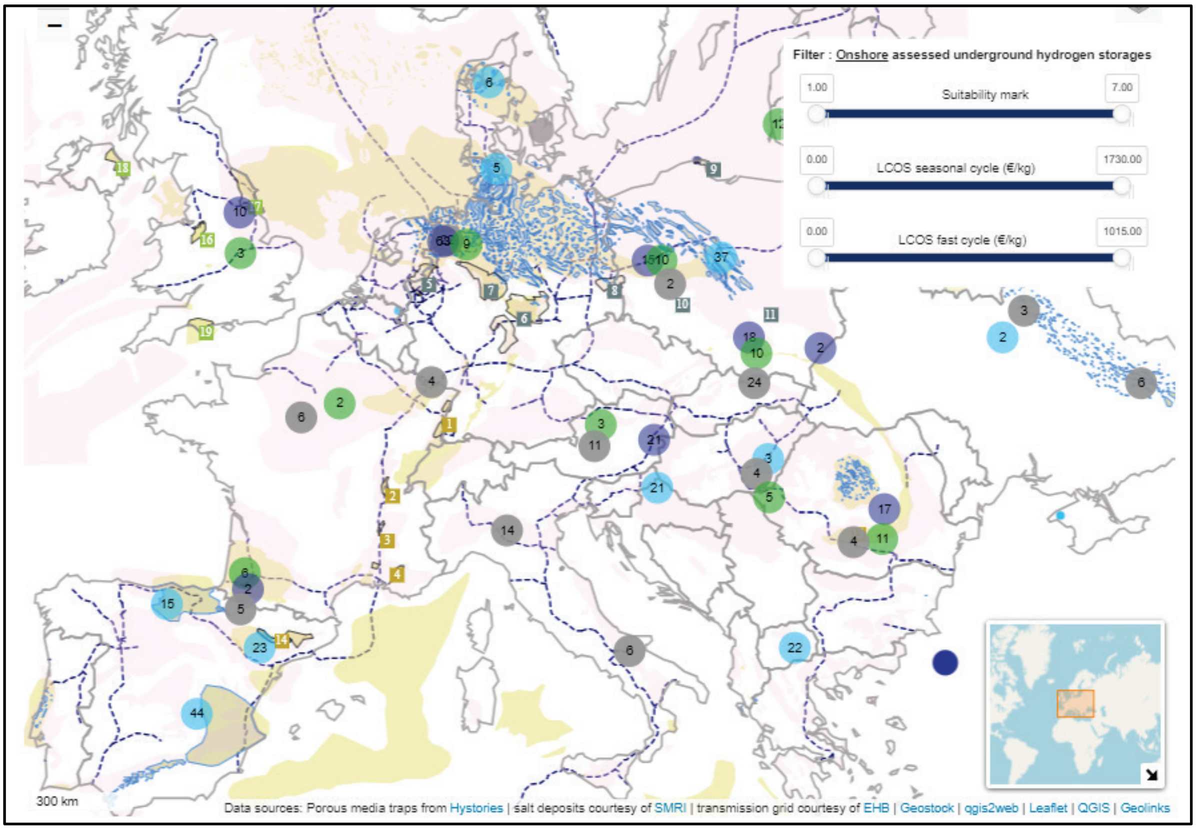

Figure 14: Hydrogen storage opportunity map, from www.hystories.eu/map

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.

[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.

Hystories project consortium

Acknowledgment

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

This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme and Hydrogen Europe and Hydrogen Europe Research

The Project is co-founded by European Union