Major conclusions and implementation plan

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1: Geostock, France

+ All the Hystories team !

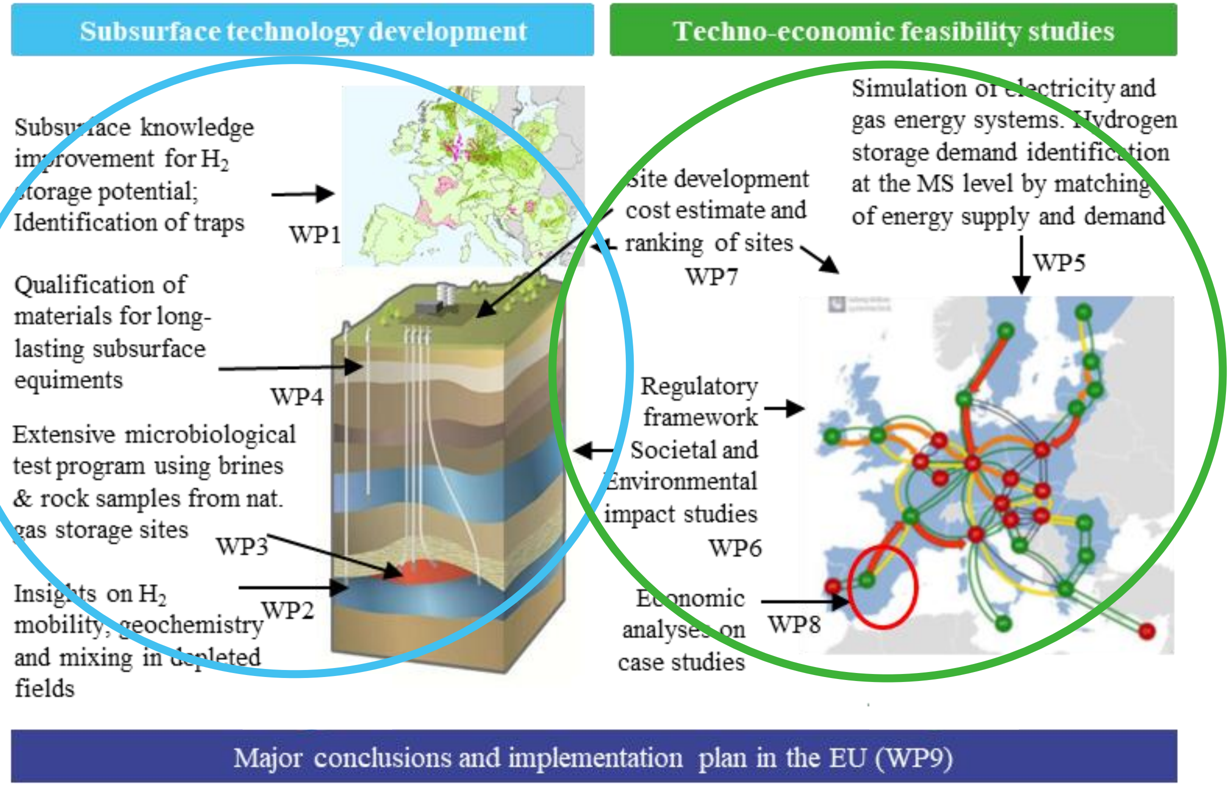
26/05/2023

Acknowledgment

The Project is co-founded by European Union

Clean Hydrogen Partnership

How mature is Underground Hydrogen Storage ?



1 – Technical maturity of porous UHS

2- Techno-economic maturity of UHS

3- Implementation plan towards an industrial deployment

4- Hystories tools for planning UHS deployment in Europe

1

Technical maturity of porous UHS

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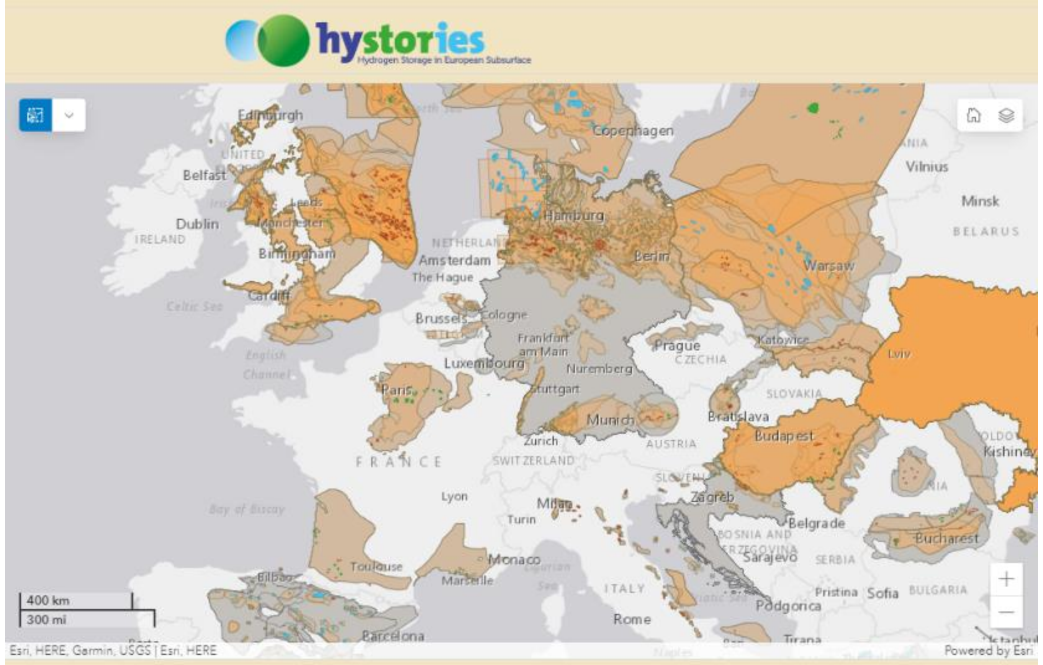
European Porous trap Geographical Information System and public database

State of the Art

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

Hystories main developments



Trap ID	Storage unit ID	Trap name	
CZ_T_20210903070420700	CZ_S_20210903070324063	Tvrdonice	Working capacity 535 mil m3 (5.71 TWh), injection 8 m3/day, withdraw 8 mil m3/
GB_T_20220208125220591	GB_S_20220208124329781	Hatfield West	Mean gross thick= arithmetic mean. Av por, perm is arithmetic mean. Av depth e
NO_T_20210920164249895	NO_S_20210920160048144	Øst Frigg N	
TR_T_20210903165204864	TR_S_20210903165109341	Sancak	POLYGON DOES NOT REPRESENT TRUE EXTENT OF THE TRAP
PL_T_20210821224217076	PL_S_20210821223849112	Grądy Bocheńskie	Lithology of reservoir: sandstones, mudstones
HU_T_20120926192314987	HU_S_20120920160624685	Babócsa IV.	parameters of the Szolnok Fm represent only the northwesternmost part of the fi
DE_T_20120927143913735	DE_S_20120927142942607	Middle Buntsandstein Daughter Unit 4	Gas field name: "Barrien" (User entered storage capacity estimation is based on
IT_T_20210715172150234	IT_S_20210708144549710	Ripalta DU	Depleted gas field, presently used as natural gas storage

Traps Table | Storage Units Table | Formations Table

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

Gaps for UHS deployment

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

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

Porous media capacity estimations

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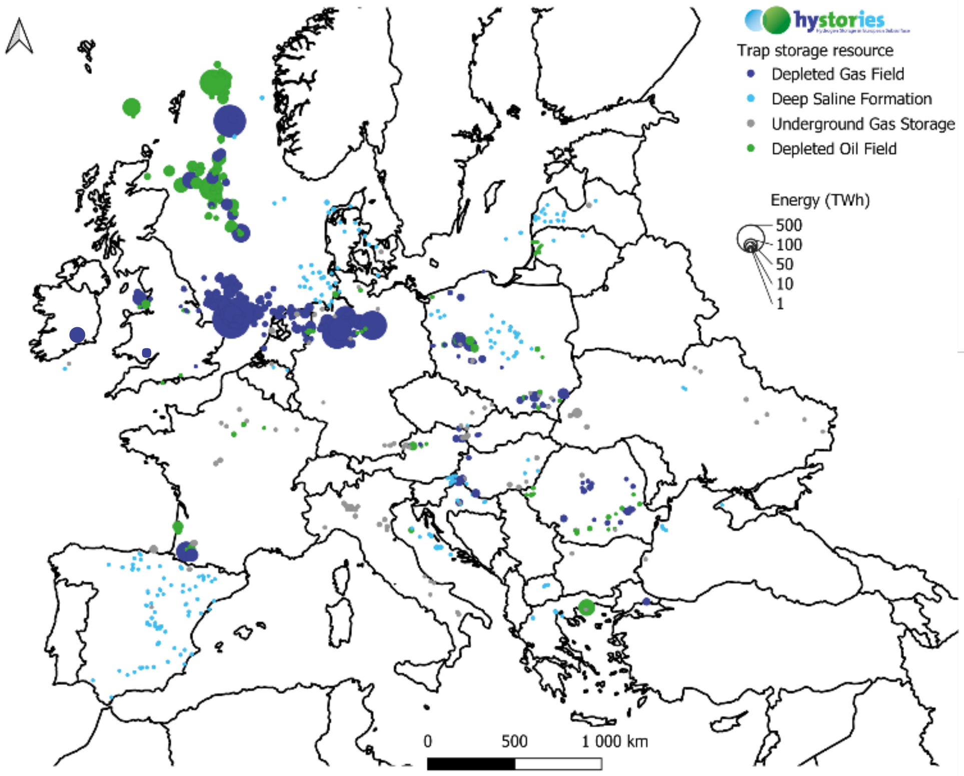
State of the Art

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

Hystories main developments



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

Gaps for UHS deployment

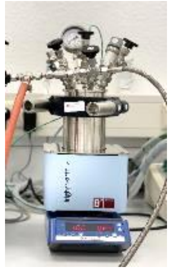
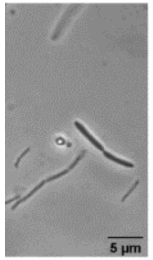
- Inherited ones from the trap database
- Storage performance for porous UHS needs industrial reference (mixing…)
  → Call for Field scale porous UHS
- Dynamic capacity estimation was done for 22 traps but required for better characterization and capacity estimation

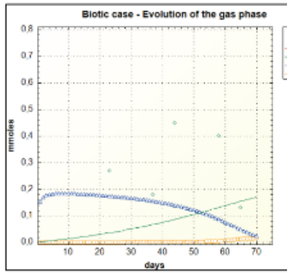
Microbiological risk assessment

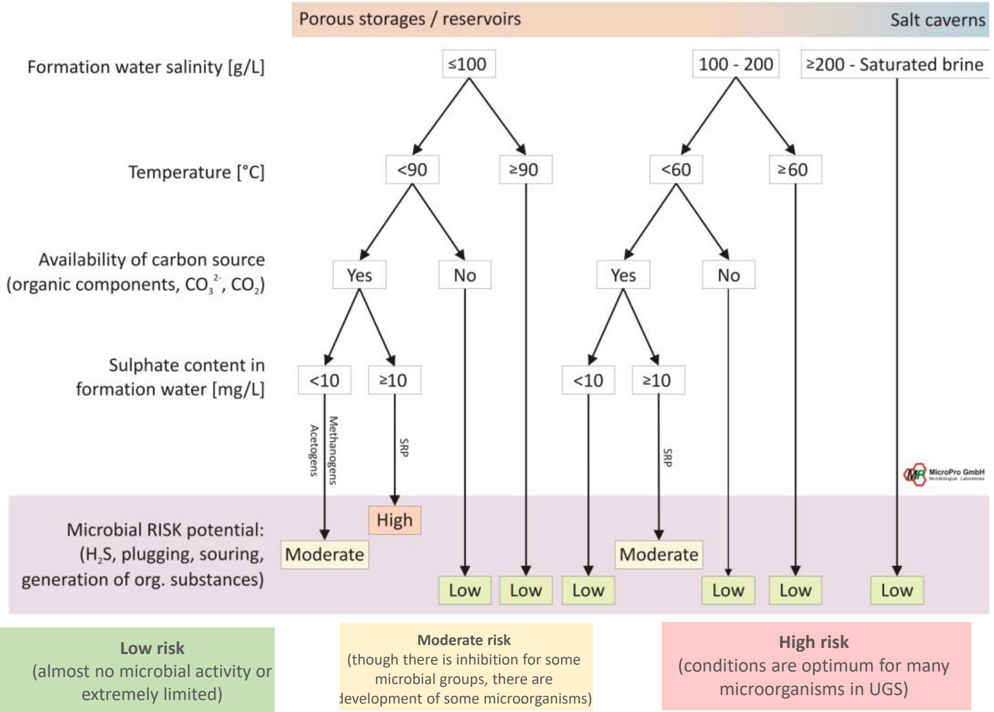
State of the Art

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

Hystories main developments





From D3.2

Gaps for UHS deployment

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

Material and corrosion

State of the Art

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

Hystories main developments

increasing yield strength

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

increasing alloy

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

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

Gaps for UHS deployment

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

2

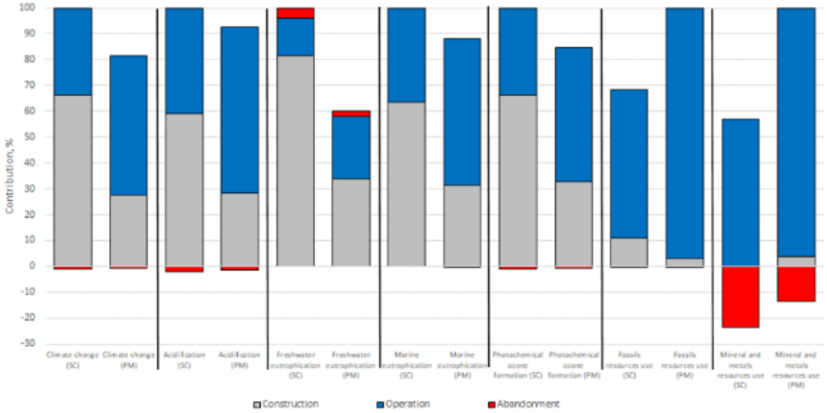
Techno-economic findings and insights

Permitting readiness, Environmental footprint and Public perception

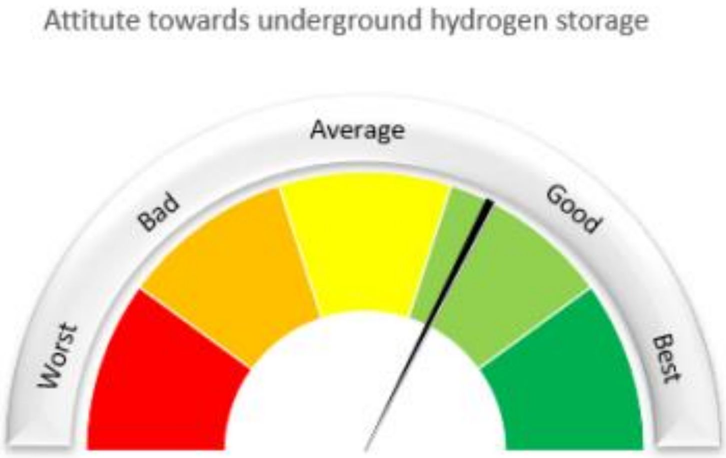
State of the Art

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

Hystories main developments



From D6.3 - Results for Environmental-LCA



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

Gaps for UHS deployment

→ Call for « Administrative experiment » through pilots

→ Call for comparison of UHS with alternative technical options

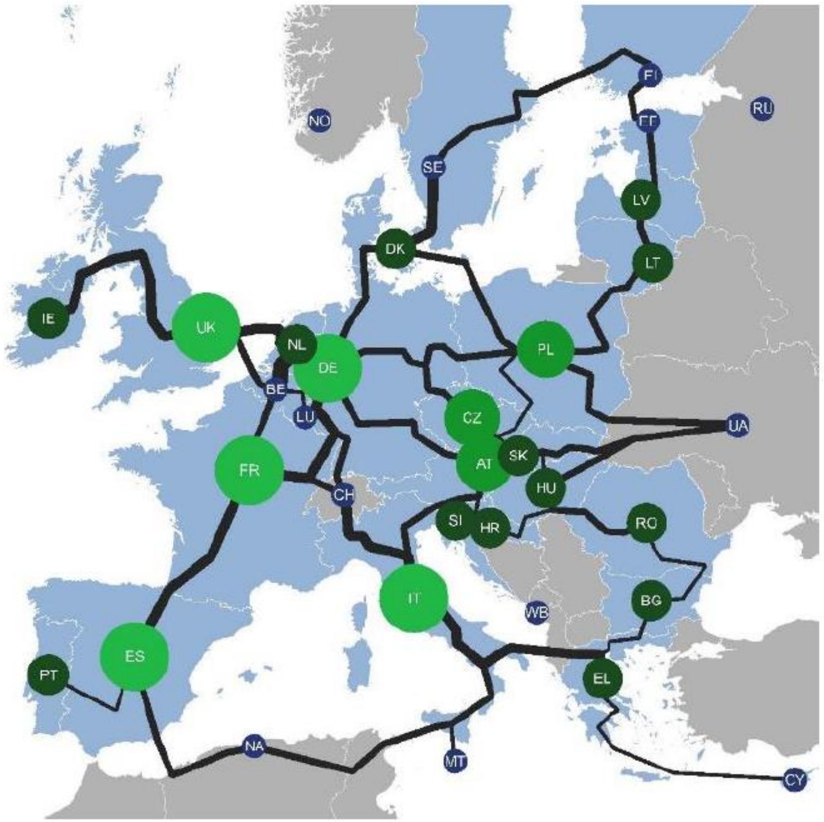
→ Call for actions promoting societal information and actions helping embeddedness for UHS

Optimal UHS for Europe

State of the Art

- Analytical analyses of storage drivers and of offtakers needs
- European scale deployment plans (not quantified regarding storage capacity need)
- Scenario-based and asumption-based projections of future hydrogen storage demand

Hystories main developments



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

Gaps for UHS deployment

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

Cost estimation

State of the Art

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

Item	Unit	Hystories 2022	HyUnder 2013	ENTEC 2022	Lord et al. 2014	DNV 2019	Ahluwalia et al. 2019
Costs							
CAPEX /energy	€/kWh	0.51	0.17	0.20	0.20	0.65	1.1
CAPEX /power	€/kW	205					
Total CAPEX for the Basis of design	€/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

Hydrogen TCP-Task 42, 2023

- Unclear boundary limits

Hystories main developments

Cost model :

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

Cost drivers	Material of construction for process parts in contact with H_2	Site specific, see chapter 0
	Total compression brake power	See chapter 4.1.2 and below formula
	Total maximum withdrawal flowrate	Site specific, see chapter 4.1.2
	Withdrawal-to-Injection Capacity Ratio (WTIR)	See chapter 4.1.2
	Maximum storage operating pressure	Site specific, see chapter 4.1.2
	Minimum compression suction pressure	See chapter 4.1.2
EPC COST	EPC_1 $[k€]$	$EPC_1 = \begin{cases} 8\,655 \cdot (1 + MCF_i \cdot 14\%) \cdot TICBP + 20\,700 \\ + 9\,100 \cdot (1 + MCF_w \cdot 11\%) \cdot Q_w{}^{0.643} \end{cases}$ With MCF_i = Material Cost Factor for injection (compression) stream; MCF_w = Material Cost Factor for withdrawal stream; $TICBP$ = Total Installed Compression Brake Power in [MW]; Q_w = Total storage maximum withdrawal flowrate in [million Sm³/day]

EPC Cost breakdown	Engineering (EMS): 14-19%	Procurement: 35-51%	Construction: 25-39%	FEED & PMC 9%

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

Gaps for UHS deployment

- No recent UHS to serve as a reference

  → Call for <u>sharing the data from industrial pilots and projects</u>

- Gas treatment cost needs particular focus. Strong impact on porous deployment. However highly site- and grid- specific

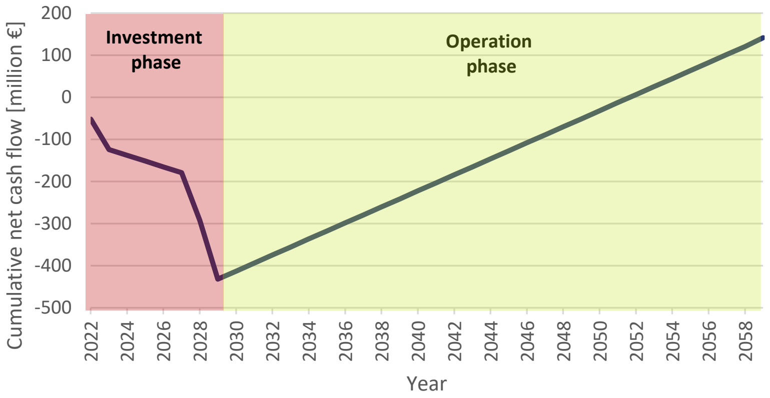
  → Call for <u>setting H2 grid specifications</u>

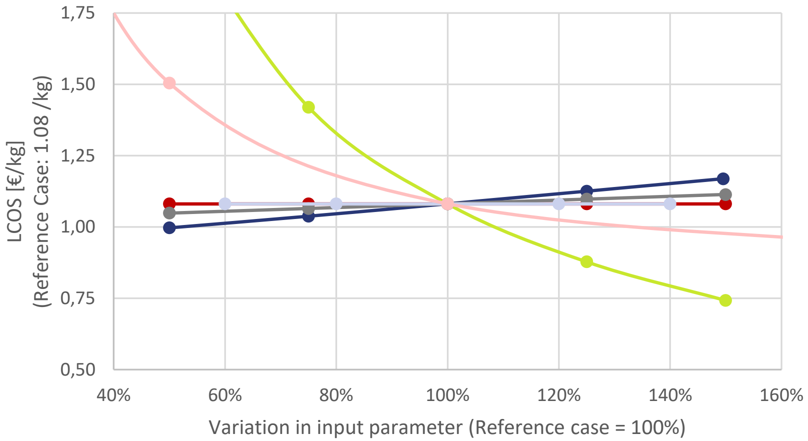
Storage market conditions for UHS

State of the Art

- No practical experiences with UHS for Net-zero objectives or for energy independence
- Experience of business frames for energy underground storage (hydrocarbons) for:
  - geopolitical reasons (oil)
  - Seasonality demand fluctuation (nat. gas)
  - Logistical / feedstock buffer (LPG, H2)

Hystories main developments





From D8.2 - European Case Studies - Germany

Gaps for UHS deployment

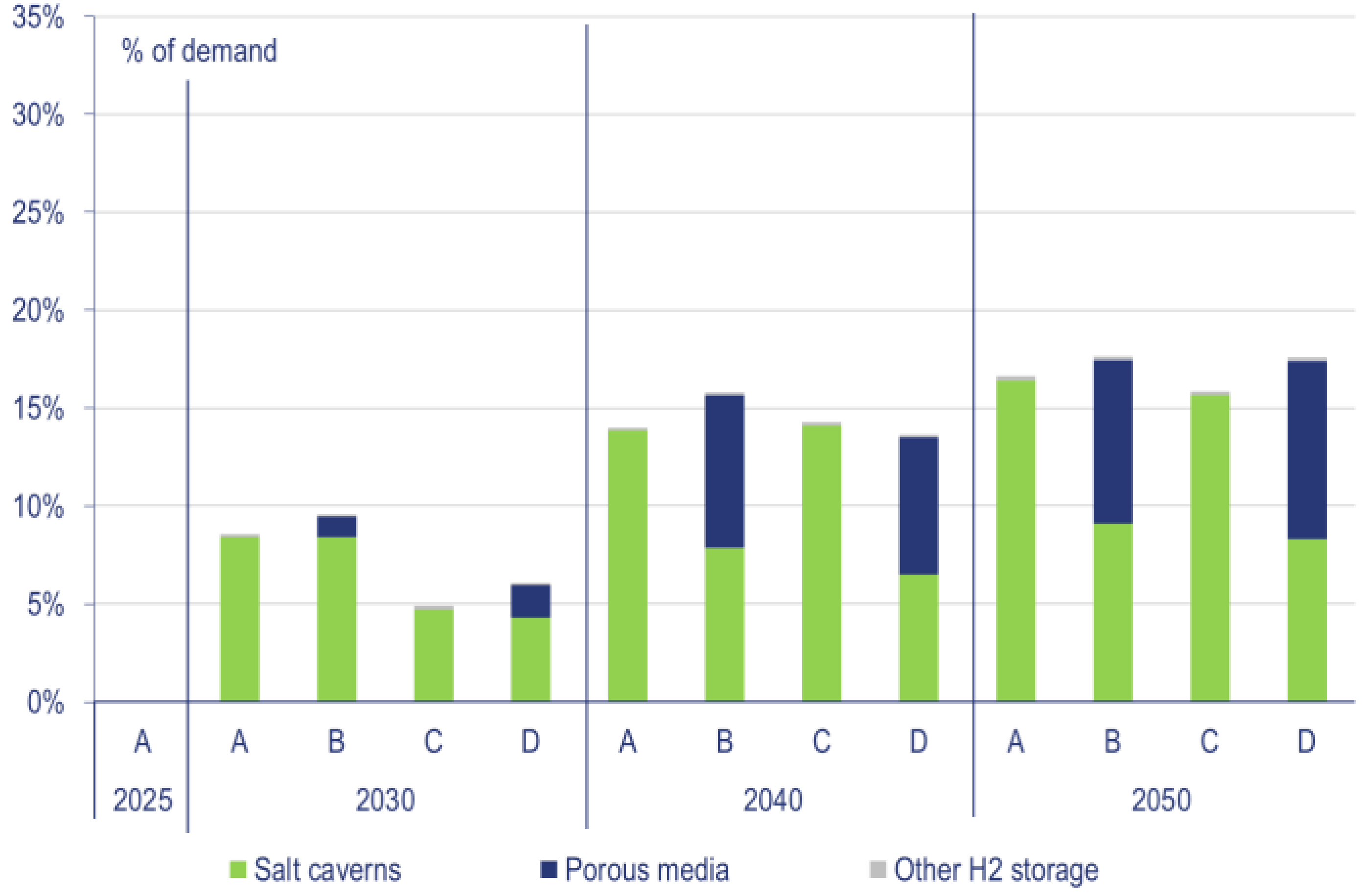
- Reduce and mitigate investment risk for early UHS projects

→ 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)

Focus : are these cost too high for UHS deployment ?

- Hystories developped 4 « costs » for both salt and porous media :
  - « €/MWh » and « €/MW » CAPEX
  - Fixed and variable parts of the OPEX
- Used in the WP5 energy system cost minimization, where UHS is only one flexibility option
- Found that the optimal deployment :
  - Involves both salt cavern and porous media storage in Europe
  - Leads to a storage capacity of 15% to 20 % of the annual demand



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

→ Even if the Levelized Cost Of Storage (1 to 3 €/kg) is close to the one of Green H2 production by 2050, the minimal overall cost of UHS translates into only 15% of the H2 supply costs

3

Implementation plan towards an industrial deployment ?

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

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- Difference in physical and chemical properties
  - Higher reactivity that is catalized by anaerobic microorganisms
  - Hydrogen embrittlement
  - lower viscosity (fingering), energy density
- Deployment spatial and time-frame
  - A major infrastructure industry has to develop in only a few decades
  - European deployment now, not national ones anymore
- Established industry vs. developping one
  - Storage drivers (supply and offtakers) are different
  - Hypothetical vs. established storage needs and cycles
  - Conceptual vs. established business cases
- Development of infrastructures in the 2030s-2050s
  - Attention for Environmental footprint, Societal embeddedness are key
- Hydrogen Storage in salt caverns (50 years experience) is seen as mature. However, technical development is not a continuous process (cf. SMRI report Buzogany et al. 2023), and « maturity » is not only technical
- No obvious show stopper for Hydrogen storage in depleted fields or aquifers. However, the purity upon withdrawal, gas treatment costs and H2 grid specifications may impact this deployment

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

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

4

Hystories insights into UHS industrial deployment

What UHS « implementation » plan should Hystories support ?

- In 2020, Call FCH-02-5-2020 saw « implementation » as insights for, possibly, a pilot

  In addition, the techno-economic feasibility of implementing hydrogen storage in preferred locations should be assessed to a level sufficient to support a decision whether or not to proceed to field pilot demonstration. This will provide substantial insights into the suitability for implementing such storage across EU and enable the development of positive business cases for adoption.

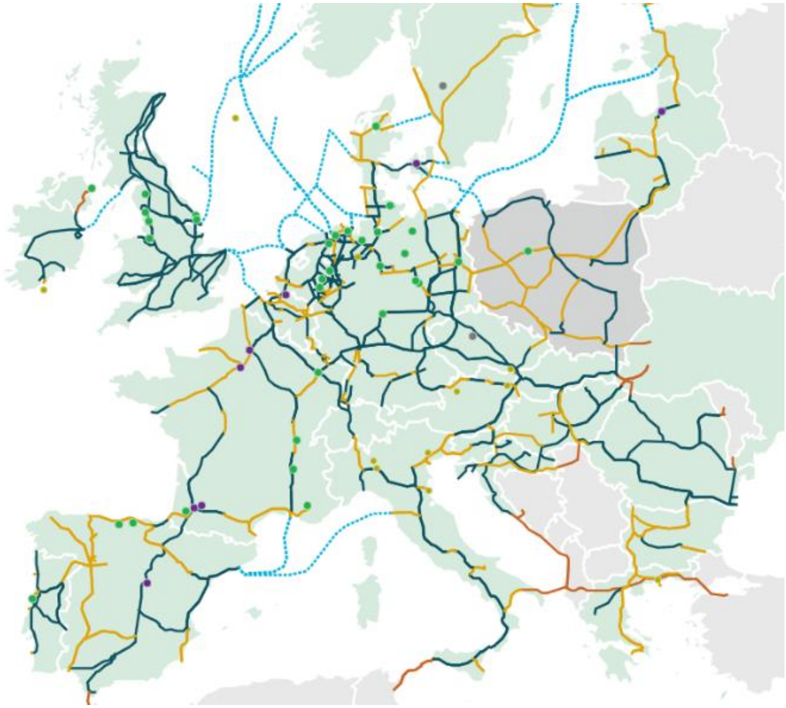
- There are 6 now !

- « Implementation » is now understood as large scale infrastructure deployment.

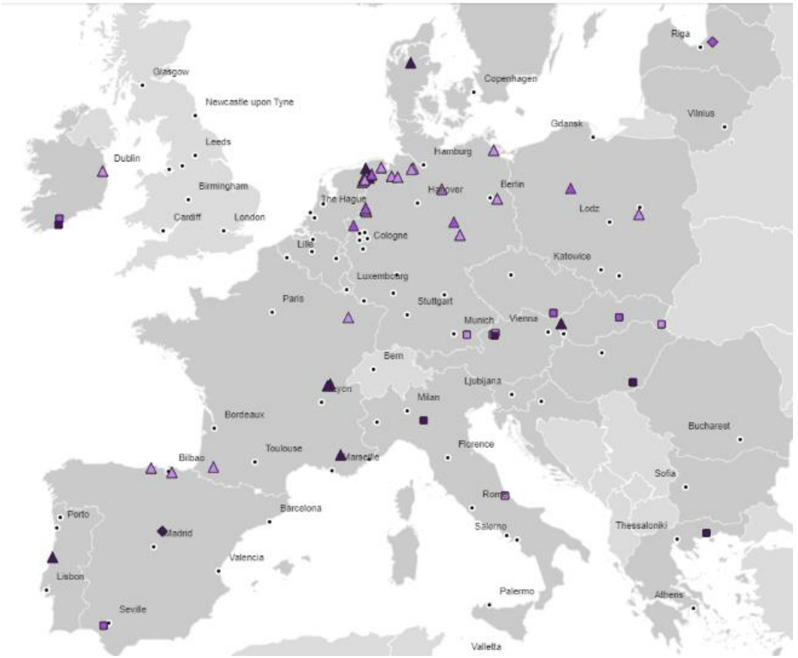
- Solving the “chicken and egg” problem is one of the most significant issues

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

Natural gas TSOs (European Hydrogen Backbone), gas industry in general (Hydrogen Infrastructure Map), and Hydrogen overall ecosystem (European Clean Hydrogen Alliance Learnbook on Hydrogen supply corridors) have been thinking and successively proposing European scale deployment plans



https://ehb.eu



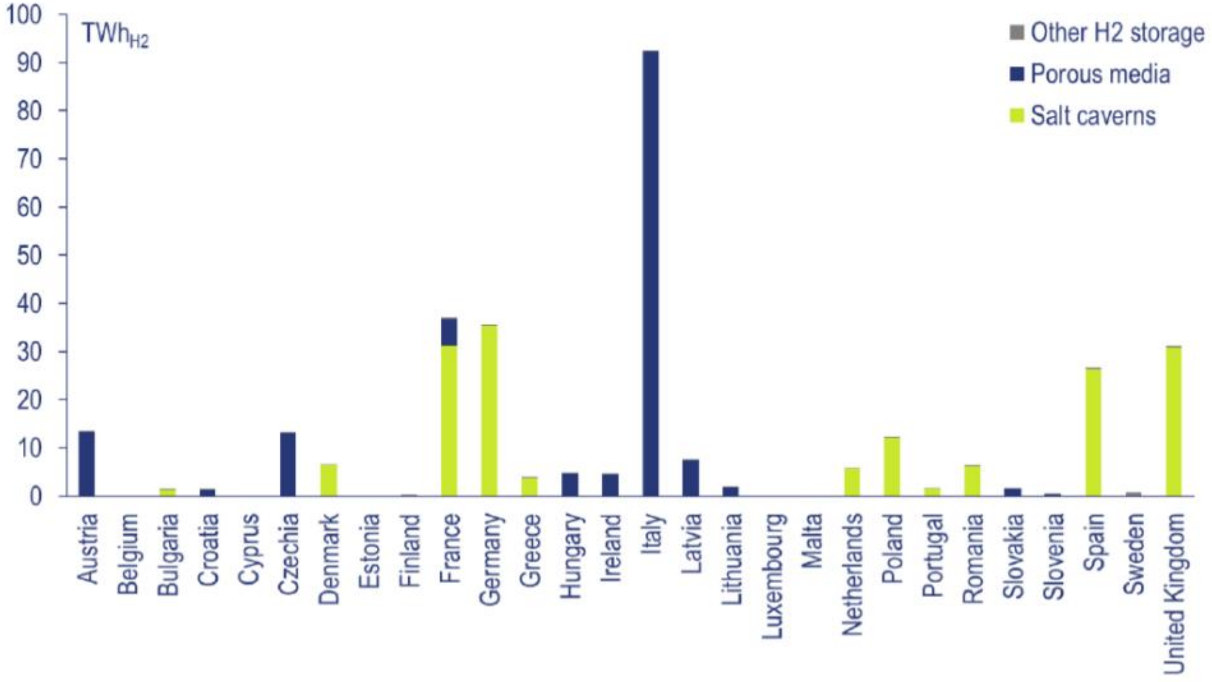
https://www.h2inframap.eu

https://www.entsog.eu

Can Hystories help ?

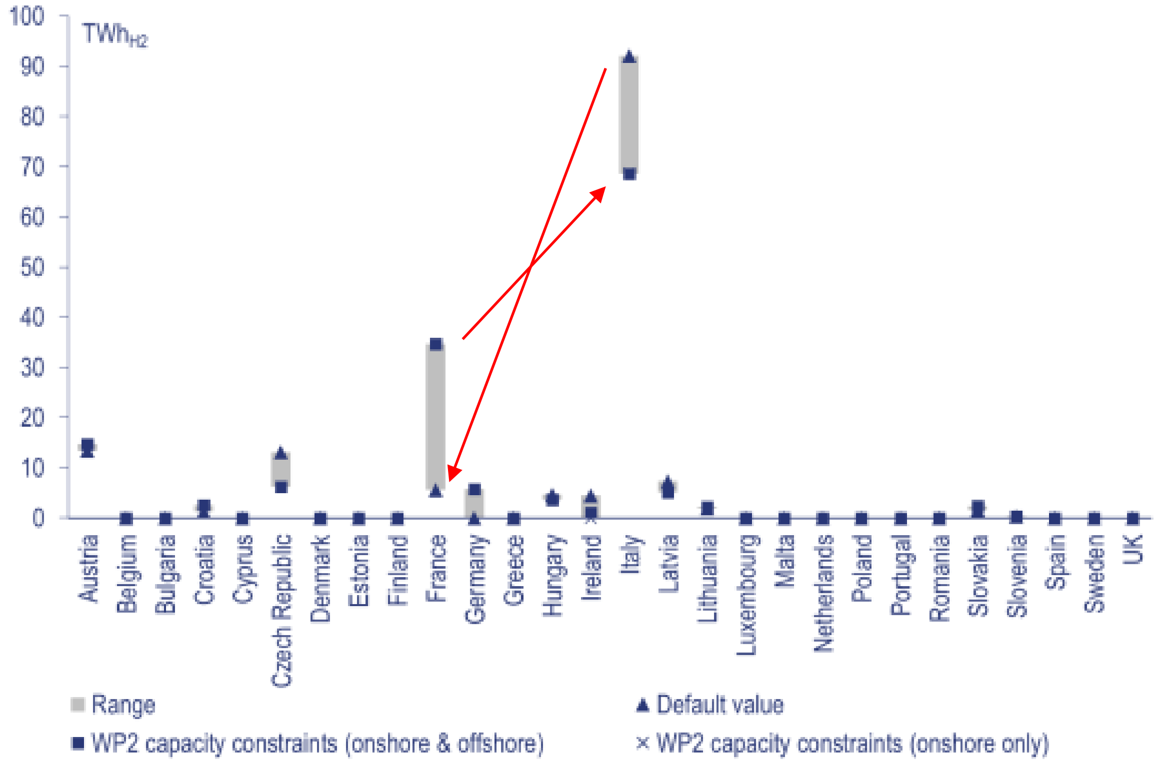
Country-specific results at EU-27 + UK scale, and pan-European sensitivities

Optimal volume capacity for hydrogen storage



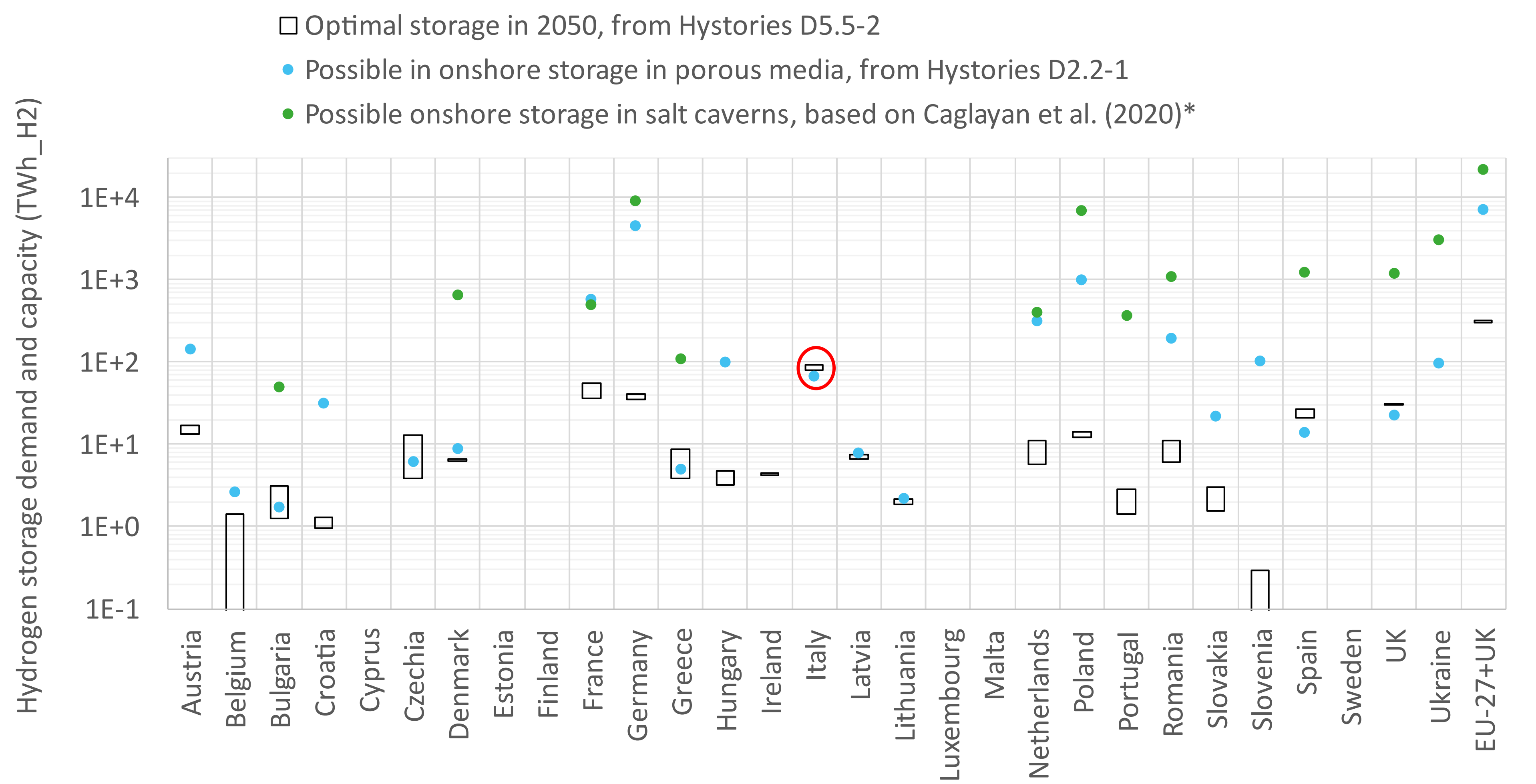
From D5.5-2 - Major results of techno-economic assessment

Optimal porous storage with capacity constraints for porous media



From D5.6-1 – Sensitivity analysis

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



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

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

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

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

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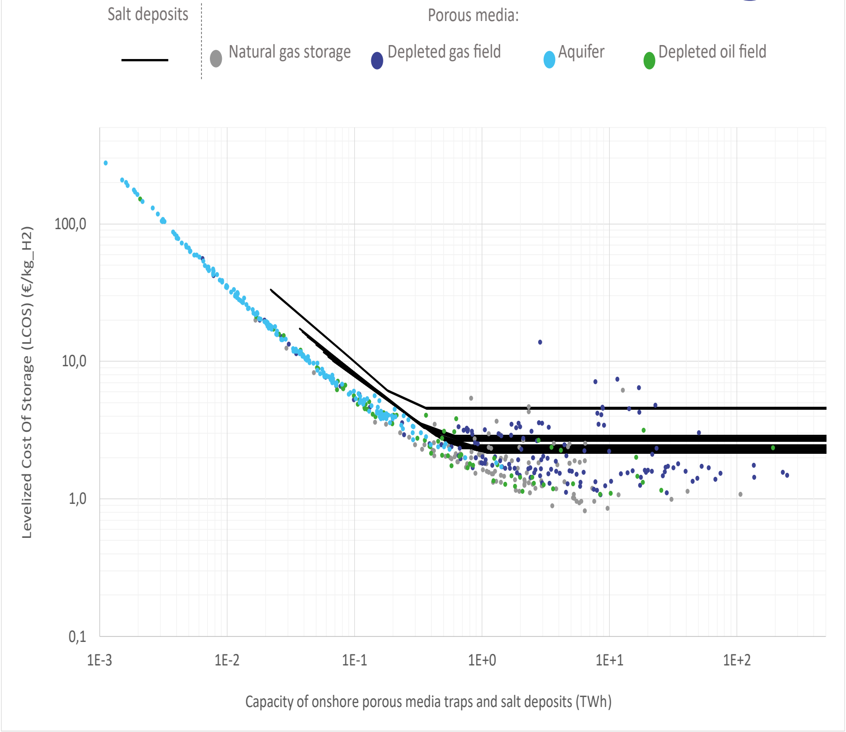
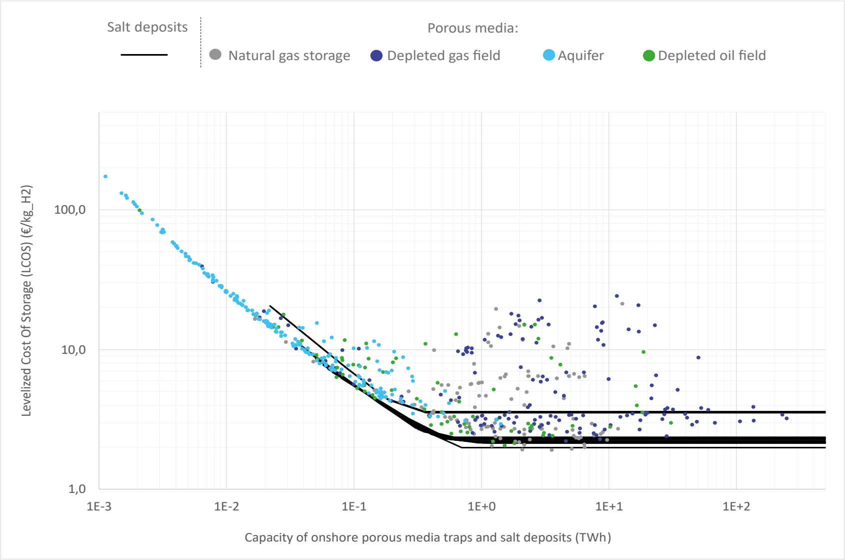
UHS cost is site-specific and cycle-specific

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

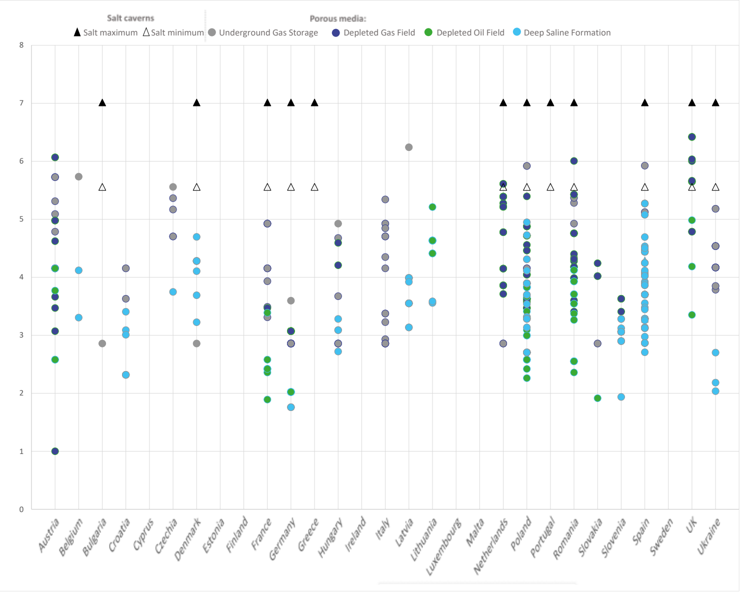
LCOS for seasonal storage



LCOS for fast storage



Suitability mark



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

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

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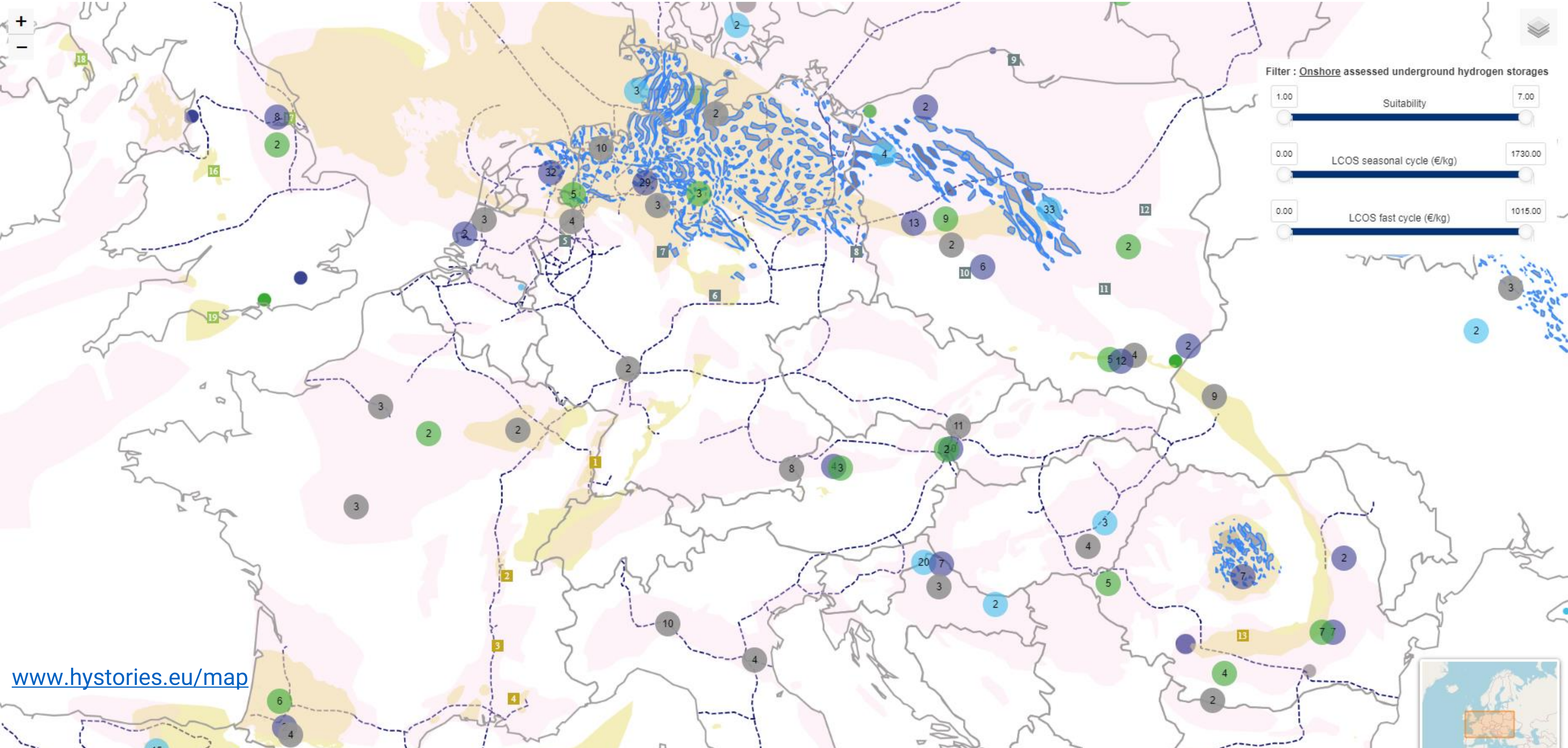

www.hystories.eu/map

Hystories project consortium

Geostock

ludwig bölkow systemtechnik

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GeoNet

MicroPro GmbH
Microbiological Laboratories

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The Project is co-founded by European Union

Clean Hydrogen Partnership

References used in this presentation

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

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Thank you !

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