Hydrogen Storage in European Subsurface

RANKING AND SELECTION OF GEOLOGICAL STORES

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Revision History

Revision	Revision date	Summary of changes
0	21 March 2023	Initial version
1	23 May 2023	Changes in the source referred to for salt cavern information. No change on the results

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1. Introduction

1.1. Need for ranking and selection

The porous media traps database resulting from Hystories Work Package (WP) 1, in D1.4, includes more than 1000 identified traps among which 750 traps in EU-27+UK (the 27 countries of the European Union and the United Kingdom) had enough data to enable capacity estimates in WP2 (D2.2-1): 229 deep saline aquifers, 267 depleted gas fields, 155 depleted oil fields and 99 existing underground gas storages. 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 D1.4 database is therefore far from including all existing traps in European Subsurface.

The Work Package 2 of Hystories (in D2.2-1) estimated the hydrogen storage capacity of each of the trap from this database. **The 750 porous media traps have a total hydrogen storage capacity of 6 925 TWh for EU-27 + UK** with only 30 TWh (0.4 %) are in Deep saline aquifers. Considering the onshore traps, the **506 porous traps represent a hydrogen storage capacity of 2 725 TWh.** As the database only includes the identified aquifer traps (even if generally not characterized enough) rather than the possibly existing ones, **this can be seen as a conservative estimation**.

Caglayan *et al*. (2020) estimate the technical storage potential of Hydrogen in Europe based on the selection of a priori suitable salt deposits in Europe and a set of reasonable assumptions. **This approach gives an upper bound of the storage potential that is technically feasible.** With only limited adjustment to this work, we estimate a **storage potential in salt caverns of 64 434 TWh for EU-27+UK, including 13 803 TWh onshore**.

Amongst all the scenarios studied in Hystories' WP5, the highest storage capacity is found for scenario D in 2050 and calls **for a hydrogen storage demand of 325 TWh in EU-27 and United Kingdom**.

The storage capacity that could technically be provided by salt caverns alone in EU-27+UK is therefore 200 times higher than the maximum storage demand, and this capacity is still 40 times higher when considering onshore salt deposits only. Depleted fields, natural gas storages in porous media and identified aquifers in EU-27+UK can technically provide almost 30 times the maximum storage demand, and this capacity is still more than 12 times higher when considering onshore structures only.

These technical storage capacities, several orders of magnitudes higher than what is needed, lead to the question of identifying which ones could be developed to meet the foreseen hydrogen storage demand. The purpose of the present report is to propose scales to rank the sites to help selecting the most favourable candidate.

1.2. Basis for ranking

A ranking is a relationship between a set of items such that, for any two items, the first is either "ranked higher than", "ranked lower than" or "ranked equal to" the second. In a one-dimensional quantitative scale, it is straightforward. The question is then how to select that one dimension.

Reducing a complex information to a single dimension scale, providing de-facto a ranking, is commonly done by assigning weights. These weight rules must be clearly stated and meaningful with the purpose of the ranking. For instance, in section 4, the weights used to merge different pieces of information into a single suitability mark are built using the Analytic Hierarchy Process.

In our case, the purpose is not always known in advance. For instance, considering two traps in the same region, of resp. 100 MWh and 10 MWh capacity, we cannot say which one is more appropriate to the need without knowing whether the local demand is higher than 10 MWh or not. The storage demand at a precise location would in most cases be known only if a project developer has a specific business plan. But for this work aiming at ranking all subsurface storage options at the European scale, it is not the case. Even though it is key for a specific project, the capacity and the storage location are therefore left out of the ranking itself. Instead, they will be displayed on a Geographical Information System (GIS) in WP9 of the project by:

- Indicating the storage capacity of each of the trap at the location of the trap, for porous media
- Indicating the salt deposit layers in the case of salt caverns.

The « storage capacity » of a salt deposit is not seen as relevant, and is not indicated, since it is largely driven by engineering and design choices: the number and size of the caverns are adapted to the required storage capacity at the desired storage location. Whereas for porous media, the capacity offered by the geological trap is a maximum for the development of a project on that trap. However, a project may choose to only develop a fraction of the traps to meet its business plan.

In this report, the ranking will be based on the following criteria:

- The cost of the underground storage
- The suitability mark, reflecting the technical readiness and level of technical risks including microbial activity given the available knowledge for developing a hydrogen storage.

Note that these two scales are built to be complementary. When the information is already accounted for in the cost criteria, it is not in the suitability mark. For instance, a depth of

4000 m leads to a poor suitability of a porous trap or a salt deposit for hydrogen storage, which is captured by the cost, but is not reflected in the suitability mark.

2. Ranking boundary limits

2.1. Data sources and countries limits

European countries included within Hystories' boundary limits are not always exactly the same. In this ranking of sites, the following data is included.

Table 1: countries included in the analysis and data source

Storage type	Information	Countries included in the present report	Source of information and explanation
Porous Media (aquifers and depleted fields)	Geological data	EU-27 + UK+ Ukraine	Hystories' WP1 work, essentially D1.2 (database of formations), D1.3 (GIS) and D1.4 (report on opportunities for geological storage of hydrogen). These works: - Include information for North Macedonia, Norway and Turkey, not used here - include information for offshore capacity, not used here - Include detailed work for some countries while for other countries, CO2Stop database is used (cf. reports for details).
	Onshore Capacity Estimate	EU-27 + UK+ Ukraine	Hystories' WP2 work, essentially D2.2-1 3D multi-realisation simulations for fluid flow and mixing issues at European scale. This work is based on the above-described geological data and covers the same countries
Salt caverns	Geological data	EU-27 + UK + Ukraine	The SMRI report by Horváth et al. (2018) is the reference used in this report.
	Onshore Capacity Estimate		Caglayan et al. (2020) is the reference used in this report. This work: - includes information for Albania, Bosnia and Herzegovina and Norway, and offshore estimates, not used here - include information for offshore capacity, not used here - was rapidly reviewed which resulted in adding data for Bulgaria and Ukraine.[1] - is notably based on a review of public information on salt deposits, most notably the collation done for SMRI in Gillhaus et al. (2006) and Gillhaus et al. (2008). These reports were then updated into Horváth et al. (2018), making it essentially coherent with the geological data source we use.
Storage Demand	Optimal demand for the European Energy System	EU-27 + UK	Hystories WP5 work, essentially D5.5 (Major results of techno-economic assessment of future scenarios for deployment of underground renewable hydrogen storages), which also requires using D5.1 (scenario definitions), D5.2 (requirements) and D5.4 (assumptions).

1 Geostock estimation for Bulgaria. Personal communication from N. Weber for Ukraine, based on his 2018 Master thesis: Weber, N., 2018. Assessment of the Technical and Economic Potential of Salt Deposits for Hydrogen Storage. Master's thesis, RWTH Aachen University. 28/09/2018.

EU-27+UK+Ukraine is therefore the area where all geological and capacity data is available. The analysis will focus on this area for all criteria. It corresponds to the initial choice to focus on EU-27+UK[2], amended to add Ukraine as all H2020 research projects were formally requested to support this country when possible. Only the storage demand is missing for Ukraine.

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[2] Note that UK was in the EU at the proposal stage and was eligible in the frame of H2020 projects including Hystories. Plus, the size of its energy system made it significative for not missing part of the European energy system

2.2. Limitation to onshore storages

The suitability mark including the assessment of the microbiological risk apply only to the geological store underground and are not impacted by its offshore or onshore condition. The cost of the storage is.

The cost model developed in D7.2-1 is based on the conceptual design (D7.1-1) which assumes green-field (new) onshore storage. Costs of developing offshore storage assets could be estimated on a project basis as well but are highly project specific. There is for instance a comparison of CAPEX for developing an onshore or offshore storage in the Dutch context in the TNO/EBN report (Van Gessel *et al.*, 2022).

Building a realistic cost model applicable to offshore cases would either be highly imprecise (e.g., applying at the European scale the offshore/onshore CAPEX ratios found for the Dutch context in the above reference) or need more than only the "offshore" or "onshore" condition as an input. Water depth and environmental settings, distance to shore would for instance be key to assess the type of structure that would be used, but this information is neither available in the salt cavern nor in porous media database (presented in the previous section 2.1).

The question was then whether applying an imprecise cost model was needed. There are several orders of magnitude more hydrogen onshore storage capacity than there is hydrogen storage demand at European level (as exposed above in section 1.1), and this finding is also true individually for these countries, except in 2 countries (Czech Republic, Italy) in some scenarios only from WP5.

The following figure compares the storage capacity requirement and the storage capacity availability onshore per country. In detail, the following data is used:

- The required storage volume capacity, from report D5.5-2. It is the hydrogen storage capacity (either salt of porous media here) that enables to minimize the overall cost of the European energy system, as found by WP5 energy modelling work and under several scenarios. The range gives the results for all scenarios (A, B, C or D).
- The storage capacity estimates in porous media, from Hystories work presented in D2.2-1. Onshore capacity only is considered.
- The storage capacity in salt caverns, based on Caglayan *et al*. (2020) and adjusted to cover EU-27+UK+Ukraine. Onshore capacity only is considered.

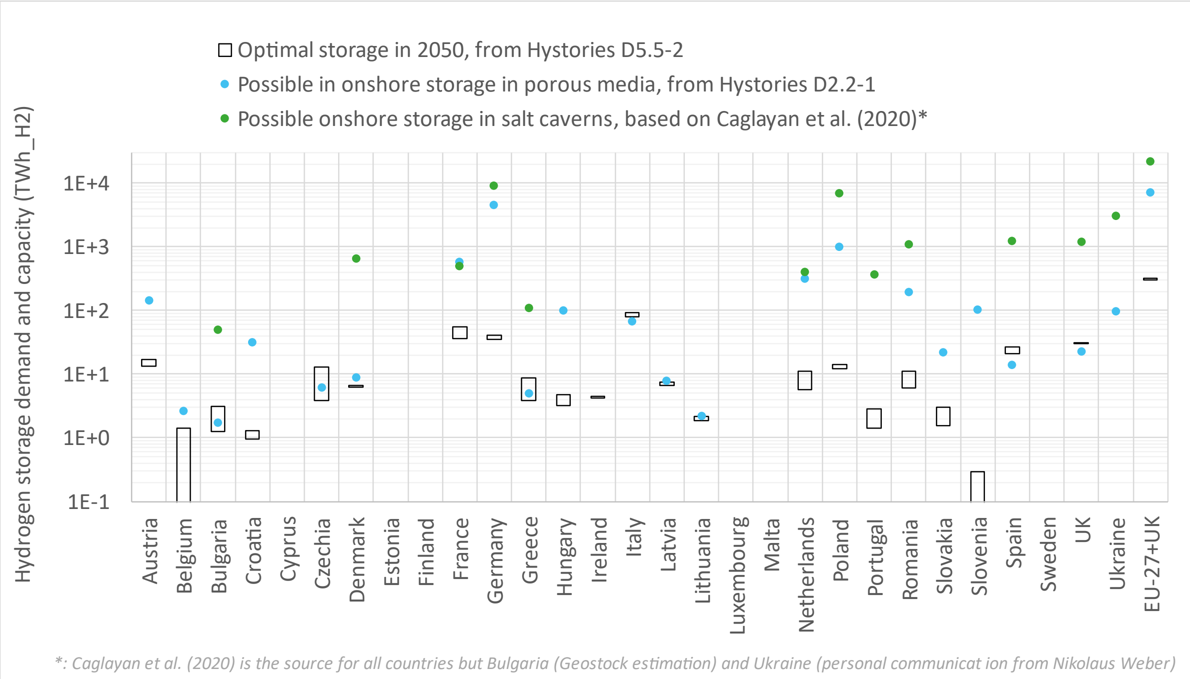


Figure 1: Optimal storage capacity in EU-27+UK+Ukraine in 2050 (scenarios B and D of WP5) and technically possible onshore storage capacity in Porous Media and Salt caverns.

While WP5 has estimated the storage demand in porous media and in salt caverns independently, both are consolidated in Figure 1, and plotted next to the capacity offered by each of these techniques. It is limited to onshore capacity since it is enough for all countries. It is actually several orders of magnitude more for most cases.

As an input of WP5 energy modelling work, the onshore + offshore storage capacity was provided for each of these countries and could have limited the storage demand. WP5 results show that onshore only is actually sufficient for all countries when salt and/or porous media are available due to the geological settings.

Last, we note that in the natural gas storage industry, offshore storage did not develop except in a handful of cases: in the International Gas Union (IGU) database, including more than 1000 facilities[3] worldwide, all but 8 are listed as onshore (all located in Europe: 1 in Greece, 1 in Ireland, 2 in Spain, 3 in UK and 1 in Turkey). Offshore is less than 1 % of the underground natural gas storages today.

For all these reasons, the cost models and suitability marks focus on onshore cases only.

[3] 2021 update of the IGU database. Note that extension of a facility is listed as a new entry, and that it includes projects. This number is therefore twice higher that what can be found in Cedigas reports.

2.3. Other limitations

The D7.2-1 cost model only considers up to 3 compression stages. When more would be needed to provide compression ratios higher than 9.67, the pressures are deemed too high and the conceptual model does not apply as such. These cases, corresponding to reservoir approaching 4000 m depth (as a rough approximation; it also depends on the reservoir pressure), are not cost estimated since their development is not judged as realistic. From the IGU database, globally, only a few sites (Grama ridge in the US and Suqaio Su1, Su4 and Su49 in China) would reach such depths, less than half a percent.

For all these reasons, in this report the cost model and the suitability mark are only applied porous media traps that do not lead to pressure requiring more than 3 compression stages.

Opportunities at very high depth and very high pressures may exist but are assumed to remain exceptional.

Last, the cost estimations are based on the application of D7.2-1 parametric cost model is able to adapt to most of the relevant parameters, but it is still far from a specific feasibility and cost estimation study on a given site. To maintain cost estimation relevant, cases are applied to basis of designs that remain acceptable for the cost model:

- For porous media, the basis for design is capped to the first design limit encountered among the following two:
    - the maximum storage capacity of the trap
    - the maximum flow rate capacity of the cost model, as specified in D7.2-1 (Table 17): 2500 ton_{H2}/day
- For salt caverns, the basis for design is the conceptual design (capacity of 250 MM Sm^3), and fractions of it (half, a quarter and $1/8^{th}$). This capacity is already a relatively large industrial storage site, the same cost is considered for sites of larger capacities. For the conceptual design capacity and the cycles considered, the maximum flow rate capacity of the cost model (2500 ton_{H2}/day) is not reached.

Costs optimizations or increases could be found, notably when site specificities differ largely from D7.1-1 conceptual design cases (for instance, very large or low-capacity sites), but a detailed feasibility study would be needed to provide a better cost estimation of these less-typical industrial sites.

3. Criteria 1: Cost of storage

3.1. Definition of the operating cycles

Underground storage could be used to store hydrogen over half a year or a couple of days; very different storage service can be provided. The design of the storage facility, and its costs, are very different as well. The “cost of storing hydrogen” needs to be properly defined by knowing which storage service is referred to. That requires defining the storage operating cycle that is considered.

There are different drivers for storing product in existing underground storage industry. Every project has its own reasons, but a typical view is that:

- CO_2 geological storage is quite specific: we do not want to recover it and should be stored for several centuries.
- Oil is stored for strategic, geopolitical, reasons. It stays stored many years to decades
- Natural gas is stored to cope for the high seasonality of the demand, leading to very seasonal cycles (cf. Figure 2 below). Although, other drivers such as trading are key in some sites, leading to shorter cycles, or strategic reasons that are there and getting more important today.
- LPGs or Hydrogen today are stored as a buffer or reserve of feedstock for industrial uses. Figure 3 presents the cycles over the first 3 years of Spindletop Hydrogen storage operation.

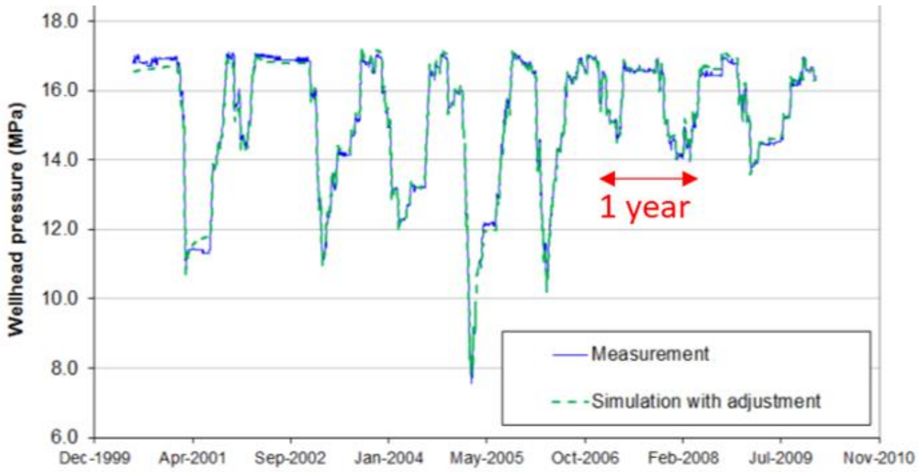


Figure 2 : Géométhane natural gas storage caverns’ cycles (Karimi-Jafari *et al*., 2013)

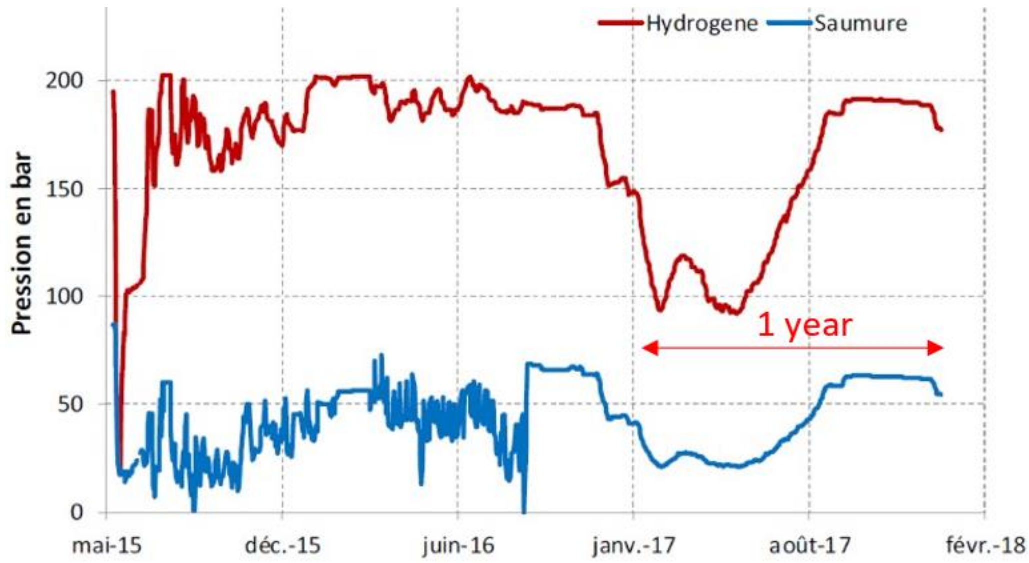


Figure 3: Air Liquide Spindletop Hydrogen storage cavern (Texas, USA). From Ineris, 2021

What are the drivers for storing green Hydrogen? Will it come from the variable demand of the offtakers? Would the offtakers be industry, mobility or the gas grid? Would it come from the supply side and the variation of the Renewable Energy production? There is no industrial experience of underground storage of green hydrogen, it was modelled in Hystories' WP5. These results lead to the definition of the cycles that are optimal for minimizing the overall system cost.

We note that in the above list of analogues, the strategic (geopolitical) reasons are for instance a major driver for a large part of the current underground storage industry. The model does not consider overcapacities of storage that would have strategic purpose, or specific location in one country.

The operating cycles derive from the drivers for storing hydrogen that should be reflected in the business plan of the storage operator. Work Package 5 of Hystories modelled the European energy system, matching energy production and energy demand at each time step introducing underground energy storage as a buffer.

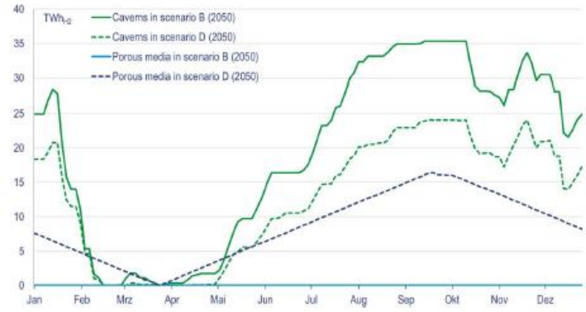
In particular, WP5 has identified scenarios of deployment of the energy system (D5.1 have made assumptions and defined input data (D5.4) and adapted their European energy system model (D5.3) to model these scenarios. Among the scenarios they have considered:

- **Scenario B:** mainly domestic H_2 production with limited H_2 imports from outside the EU
- **Scenario D:** smaller share of domestic H_2 production in comparison to Scenario B and therefore with larger share of H_2 imports to Europe.

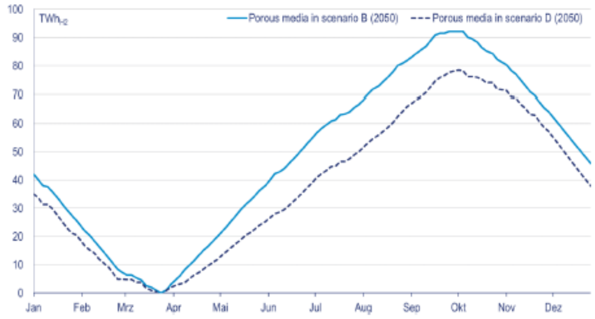
The result of this energy modelling exercise are the working conditions of this energy system at minimized cost, or in optimal conditions. Results include the optimal storage capacity and injection/withdrawal capacity per country, as exposed in D5.5-2.

It also includes the optimal cycle. It is for instance given in section 7.5 for 5 countries, as depicted in the Figure 4 below for scenarios B and D in 2050:

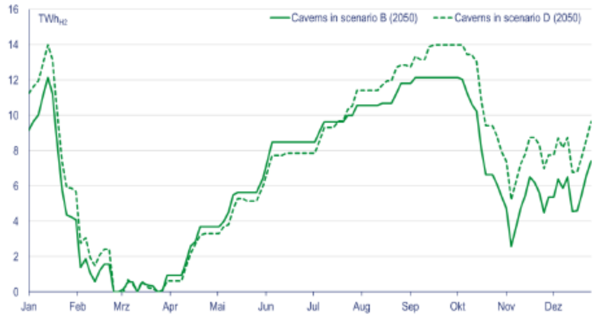
France



Germany



Italy



Spain

Poland

Figure 4: Optimal cycles in 2050 as found by the energy modelling work of WP5, for scenarios B (mainly domestic Hydrogen production) and D (with a larger share of imports) for France, Germany, Italy, Spain and Poland. (Hystories D5.5-2)

These plots illustrate that the optimal cycles found for year 2050. We notice:

- That the cycles are essentially seasonal. This is even nearly strictly seasonal, with a continuous injection or withdrawal of the stored hydrogen in the case of porous media storage. Salt cavern storage show a general seasonal trend that also accommodates for shorter term cycles within it.
- For France and Germany, the two countries where both salt caverns and porous media are developed in some scenarios, operations are steadier over time for porous storages (blue curves) with very few stand-by while for salt cavern storage, the cycles are characterized by the presence of stand-by time and by a high number of small injection and withdrawals to meet fast market demands. So these cycles differences are related to the storage technology (salt caverns vs. porous media) rather than on the country storage demand.

We notice that this is observed as well in the natural gas storage market. It is somehow expected and shows that the cost model that was built in D7.2-1 together with the WP5 energy modelling enable to capture the main mechanisms of the market. This derives from the cost structure of both technologies, an output of D7.2-1 and an input of WP5:

- The CAPEX of the storage capacity is 0.51 €/kWh_H_2 for salt caverns and 0.20 €/kWh_H_2 for porous storages based upon the conceptual designs
- The CAPEX of the storage withdrawal capacity is 205 €/kW_H_2 for salt caverns and 645 €/kW_H_2 for porous storages based upon the conceptual designs

The minimal overall cost for the European energy system found in WP5 corresponds to having seasonal storage in porous storages (since the cost of storage capacity is cheaper), and shorter cycles in salt caverns (since the cost of withdrawal capacity is cheaper).

The stock fluctuation over time of Figure 4 enables a qualitative understanding of the buffering role expected for Hydrogen underground storage. The highly seasonal trend is quite similar to natural gas, despite the fact that the drivers differ: it is dominated by the same seasonality of demand as natural gas, while other drivers, such as the seasonality of production, are also at play for hydrogen.

The WP5 work also enables a more quantitative estimation of the cycles. First, it gives the number of full cycle equivalents per year: in a purely seasonal cycle, the amount of hydrogen transiting into the storage equals the storage capacity. But the storage can be more active, and 2, 3 times the storage capacity can transit in the storage. This is captured by the table "Number of full cycle equivalent" that are given explicitly in D5.5-2 for salt caverns (p. 68) and porous media (p. 69), and therefore not reproduced in the present report.

From D5.5-2, additional characterization of the operating cycles can be made. Notably, the definition of Withdrawal to Injection ratio (WTIR, as defined in D7.2-1), a key design parameter to size the injection facilities (mostly compressors) relatively to the withdrawal ones (notably dehydration units). This interpretation is given in Table 1.

Table 2: Optimal Withdrawal to Injection ratio (WTIR, as defined in D7.2-1) of underground storages found by WP5 energy modelling work for scenarios B and D (cf. D5.5-2)

	Salt caverns						Porous media					
Scenario	B	B	B	D	D	D	B	B	B	D	D	D
Year	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Austria								1.0	1.0		1.0	1.0
Belgium												1.0
Bulgaria	13.7		1.0	3.0		2.1		1.0			1.0	1.0
Croatia							6.3	1.0	1.0	1.0	1.0	1.0
Cyprus												
Czechia							1.0	1.0	1.0	0.4	1.0	1.0
Denmark	1.0	1.0	1.8	0.9	1.0	2.6						
Estonia												
Finland												
France	0.8	1.0	3.5	1.0	1.0	3.0		1.0	1.0		1.0	1.0
Germany	1.0	1.0	3.2	1.0	1.0	3.2						1.0
Greece	14.5	1.0	1.1	5.3	1.0	2.0		1.0			1.0	
Hungary							6.0	1.0	1.0	1.0	1.0	1.0
Ireland							0.1	1.0	1.0	0.9	1.0	1.0
Italy							3.1	1.0	1.0	1.0	1.0	1.1
Latvia							0.3	1.0	1.0	1.0	1.0	1.0
Lithuania							0.9	1.0	1.0	1.0	1.0	1.0
Luxembourg												
Malta												
Netherlands	1.0	1.0	1.2		1.0	2.0						
Poland	1.0	1.0	2.4	1.0	1.0	2.8						
Portugal	0.5	1.0	1.0	0.5	1.0	1.0						
Romania	10.3	1.0	1.5	1.9	1.0	2.0		1.0			1.0	1.0
Slovakia								1.0	1.0		1.0	1.0
Slovenia							3.4	1.0	1.0	1.0	1.0	1.0
Spain	1.0	1.0	1.0	1.0	1.0	1.0		1.0			1.0	
Sweden												
United Kingdom	0.2	1.0	1.9	0.7	1.0	1.7						
EU27 + UK	0.8	1.0	2.1	0.9	1.0	2.2	1.2	1.0	1.0	0.9	1.0	1.0

Another key design parameter is the Load Factor, i.e. the percentage of time in the year the storage facility is not in stand-by[4]. The Load factors resulting from the WP5 optimization are given in the Table 2:

Table 3: Optimal Load Factor (the percentage of time in the year the storage facility is not in stand-by) of underground storages found by WP5 energy modelling work for scenarios B and D (cf. D5.5-2)

	Salt caverns						Porous media					
Scenario	B	B	B	D	D	D	B	B	B	D	D	D
Year	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Austria								87 %	94 %		88 %	91 %
Belgium												95 %
Bulgaria	82 %		40 %	43 %		34 %		95 %			97 %	95 %
Croatia							56 %	83 %	86 %	39 %	88 %	83 %
Cyprus												
Czechia							61 %	89 %	93 %	89 %	90 %	85 %
Denmark	54 %	53 %	24 %	57 %	53 %	28 %						
Estonia												
Finland												
France	49 %	41 %	31 %	53 %	47 %	27 %		95 %	97 %		97 %	94 %
Germany	35 %	34 %	25 %	40 %	33 %	26 %						97 %
Greece	59 %	60 %	15 %	51 %	73 %	25 %		94 %			93 %	
Hungary							55 %	96 %	88 %	50 %	90 %	86 %
Ireland							82 %	86 %	79 %	68 %	88 %	75 %
Italy							49 %	83 %	76 %	37 %	83 %	63 %
Latvia							52 %	45 %	39 %	59 %	46 %	36 %
Lithuania							63 %	49 %	43 %	78 %	53 %	37 %
Luxembourg												
Malta												
Netherlands	43 %	46 %	19 %		38 %	23 %						
Poland	40 %	55 %	30 %	44 %	54 %	33 %						
Portugal	60 %	64 %	24 %	64 %	56 %	40 %						
Romania	80 %	46 %	22 %	45 %	57 %	33 %		95 %			95 %	88 %
Slovakia								91 %	93 %		92 %	92 %
Slovenia							39 %	88 %	95 %	50 %	89 %	94 %
Spain	40 %	56 %	39 %	44 %	58 %	44 %		93 %			93 %	
Sweden												
United Kingdom	75 %	54 %	30 %	81 %	57 %	31 %						
EU27 + UK	46 %	50 %	27 %	58 %	54 %	29 %	45 %	79 %	72 %	62 %	79 %	68 %

4 We use in this deliverable the « Load Factor » as defined in D7.2-1. Note that it assumes that the storage operates only at full injection or withdrawal capacity

The last design parameter that is used is the Storage to Withdrawal Capacity ratio, which is given in days[5]. The Storage to Withdrawal Capacity ratio resulting from the WP5 optimization are given in the Table 3:

Table 4: Optimal Storage to Withdrawal Capacity ratio (in days) of underground storages derived from WP5 energy modelling work for scenarios B and D (cf. D5.5-2)

	Salt caverns						Porous media					
Scenario	B	B	B	D	D	D	B	B	B	D	D	D
Year	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Austria								159	171		161	166
Belgium												173
Bulgaria	16		24	16		26		173			177	173
Croatia							34	152	158	34	160	151
Cyprus												
Czechia							35	162	170	115	164	154
Denmark	31	25	11	29	27	11						
Estonia												
Finland												
France	35	53	20	31	52	16		174	176		177	171
Germany	11	35	15	17	43	14						176
Greece	11	74	11	16	92	21		171			169	
Hungary							34	175	161	34	164	156
Ireland							320	110	104	60	110	96
Italy							44	152	138	49	151	111
Latvia							136	51	38	43	52	34
Lithuania							62	63	36	44	74	34
Luxembourg												
Malta												
Netherlands	22	44	11		53	16						
Poland	19	32	14	21	35	15						
Portugal	85	92	36	72	72	48						
Romania	20	66	21	19	79	32		173			173	161
Slovakia								166	167		168	167
Slovenia							34	160	173	35	163	172
Spain	28	82	53	35	85	57		169			170	
Sweden												
United Kingdom	133	33	13	56	34	15						
EU27 + UK	37	47	17	38	48	18	54	136	122	52	135	115

[5] It is expressed in hours (i.e. GWh/(GWh/h) or $Sm^3/(Sm^3/h)$) in D7.1-1 or D7.2-1.

Table 3 highlights the very different storage services provided by salt caverns and porous media: while salt caverns are found to have a withdrawal capacity of all their stock in 18 days, less than 3 weeks (at EU-27 + UK scale), porous media need 115 days, i.e. 4 months. Exceptions are found for Latvia and Lithuania, where salt cavern storage is not an option.

Different cycles could be considered for closer horizons or specific countries. These cases can be built from the tables above. In the following, the focus is on Scenario D. The reason is that the scenarios were first defined within D.5.4-0 a few days before the invasion of Ukraine by Russia. Since then the European Commission published the REPowerEU Plan, "its response to the hardships and global energy market disruption caused by Russia's invasion of Ukraine", that notably sets "a target of 10 million tonnes of domestic renewable hydrogen production and 10 million tonnes of imports by 2030, to replace natural gas, coal and oil in hard-to-decarbonise industries and transport sectors."[6]. This objective is closer to the import hypotheses of Scenario D (cf. Table 1 of D5.4-1).

In the following, the ranking therefore focuses on two cycles:

- Operation cycle 1:
  - 1.1 full cycle equivalent per year. Approximately the storage capacity transits through the storage every year
  - Load Factor = 68 %. The storage facility is active (injecting or withdrawing) 68 % of the time (i.e., 8 months of activity during which 1.1 full injection and withdrawal cycle is performed, and 4 months of stand-by).
  - Withdrawal to Injection Ratio (WTIR) = 1.0. The storage facility is designed to have the same injection and withdrawal flow rate capacity.
  - Storage to Withdrawal Capacity ratio ≅ 115 days. The storage can be totally emptied in about 4 months.
- Operation cycle 2:
  - 1.9 full cycle equivalent per year. The total hydrogen transiting into the storage is approximately twice the storage capacity.
  - Load Factor = 29 %. The storage facility is active (injecting or withdrawing) 29 % of the time (i.e., 3 and a half months of activity during which the 2.2 full cycles are performed, and 8 and a half months of stand-by).
  - WTIR = 2.2. The storage facility is designed to enable withdrawal being twice faster than injection.
  - Storage to Withdrawal Capacity ratio ≅ 18 days. The storage can be totally emptied in 2.5 weeks.

6 https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3131

Operation Cycle 1 is typically the optimal use that is found by WP5 model for porous media in Europe in 2050, scenario D. Operation Cycle 2 is typically the optimal use that is found by WP5 model for salt caverns in Europe in 2050, scenario D. However, projects are not bonded by any of these cases: it is possible that some salt cavern storage sites cycles will be close to Operation Cycle 1 (there is no technical challenge for salt caverns to operate smooth seasonal cycles), and porous storage sites cycles close to Operation Cycle 2 (although it can be technically more difficult for some low transmissivity porous reservoirs to operate on fast cycles. But it is possible in good reservoirs and is assumed possible here).

3.2. Levelized Cost of Storage (LCOS) definition and main assumptions

The Levelized Cost of Storage (LCOS) is estimated as a net present value of the total costs divided by a net present value of the quantity of H_2 transit over a project lifetime. The operational lifetime is assumed to be 30 years for all projects.

The formula used for the calculations is:

$$LCOS = \frac{\sum(CAPEX_t + OPEX_t + ABEX_t) \cdot (1+r)^{-t}}{\sum H2transit_t \cdot (1+r)^{-t}}$$

Where:

- CAPEX is as described in D7.2-1. For sites whose storage capacity leads to exceeding the limits set in D7.2-1 (the injection flow rate of 30 MM Sm^3/d), the limit is considered. The CAPEX is split into the surface and subsurface components. Each component is assumed to be equally spread over the construction period. The main hypotheses for the spread of the CAPEX spending are as follows:
  - The surface CAPEX is evenly spread over 2 years for the surface facilities.
  - For the subsurface facilities, the CAPEX is evenly spread over the construction duration. The construction duration is based on the drilling rig mobilisation per well, the number of wells to be drilled, and for the salt caverns on the leaching and first gas fill durations. The drilling and leaching durations are set according to the hypotheses described in D7.1-1 and D7.2-1. Notably, in the case of a salt caverns storage site, the caverns are leached by successive batched of 4: for example, in an 8-caverns storage site, the leaching of the 2nd batch of caverns only starts after the first batch is leached.
  - The start of the construction periods of the surface and subsurface facilities are optimized in order to have both end at the same time, for the start of the operational phase.
- OPEX includes Fixed OPEX per year (both surface and subsurface) and Variable OPEX based on the hydrogen transit per year.
- The ABEX (Abandonment Expenditure) is defined in D.7.2-1. It is assumed to be equally spread over a 2-year decommissioning period at the end of the operations.

- Facility lifetime is considered to be 30 years.
- The H_2 transit is the quantity of hydrogen (in kg) that has been withdrawn from the storage. In the case of salt caverns storage sites, the H_2 transit ramps up according to the batch of caverns that have come into operation. In the case of porous media storage, the fact that part of the hydrogen might not be recovered is taken into account by applying the H_2LossPorous coefficient as defined in D7.2-1.
- "r" is a discount rate for the project, which is assumed to be 8 % per annum in real terms.
- It should be noted that the calculations have been done in real terms i.e., no inflation has been added to the numerator and the denominator of the LCOS formula.

  For the Conceptual Design of D7.1-1, this leads to the following cost estimation:

  - LCOS for the Operation Cycle 1 (seasonal cycle) is 2.7 €/kg for salt cavern and 2.1 €/kg for porous storages.
  - LCOS for the Operation Cycle 2 (fast cycle) is 2.3 €/kg for salt cavern and 2.7 €/kg for porous storages.

3.3. Conversion of existing sites to hydrogen underground storage facilities

The cost model developed in D7.2-1 relies on a conceptual design of a new underground storage site, for salt cavern and porous media.

Conversion of an existing underground natural gas storage can be considered as well and will even possibly provide first opportunities to develop underground hydrogen storage. Technically, the conversion from gas storage to hydrogen storage would be highly specific to the context, and to the underground. For salt caverns, it would for instance be impacted by the availability of water or brine for rebrining. For porous media, less operations may be needed on the underground part, possibly with a re-purposing of production and monitoring wells, but separation would be needed when withdrawing. And, in any case, the current underground natural gas storage is an asset worth something. This value is estimated in our model by assuming that the cost of purchase and conversion of an existing natural gas storage site is the cost of an equivalent green field storage.

Besides the natural gas storage industry, gas and brine production industries may also provide respectively depleted fields and brine caverns assets that can be re-used for hydrogen storage. Similarly, the cost of such re-use corresponds to the purchase of this asset and the cost of the conversion works. This overall cost is also assumed to be the cost of a new equivalent green field storage.

Therefore, the cost model of D7.2-1, corresponding to a new site as designed in D7.1-1, is applied to all new and conversion cases.

3.4. Assumptions used for the application of the LCOS to salt deposits

The source of information for the salt deposits is SMRI Research report and GIS Horváth et al. (2018). The contours of the deposits that are assessed are represented in the figure below, and are coherent with the deposits selected in the technical storage capacity estimation by Caglayan et al. (2020) with minor changes as detailed in §2.1.

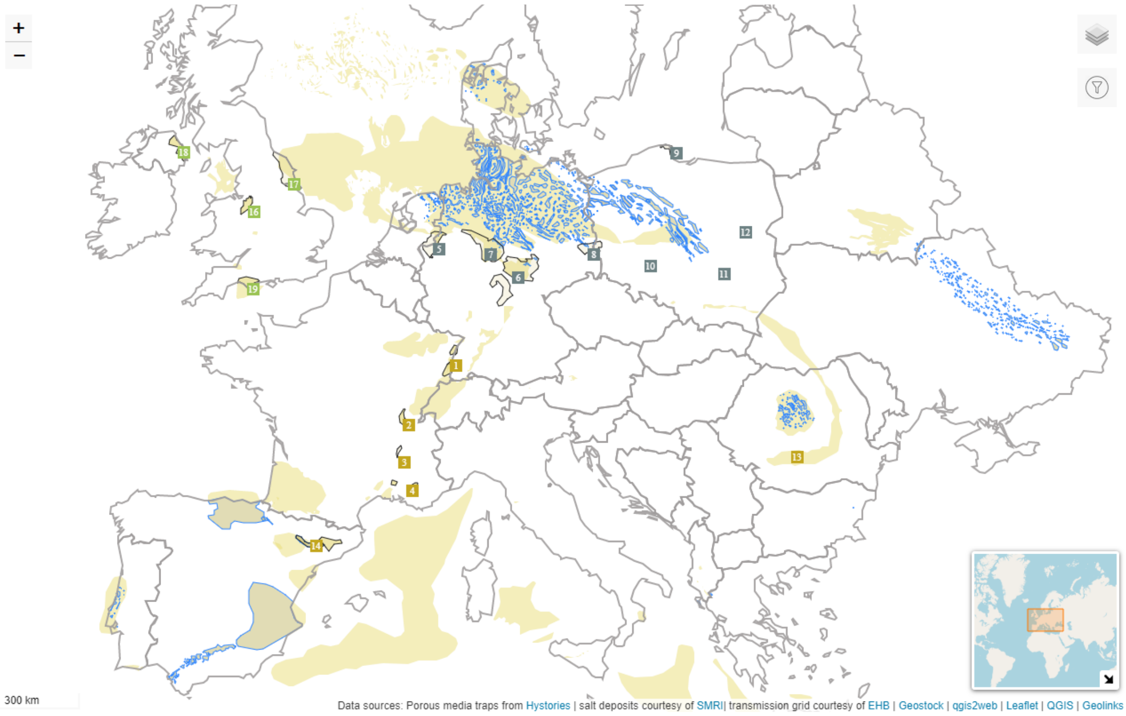


Figure 5: Bedded salt deposits (numbers), salt domes or deposits partly with salt domes (blue contours), and overall salt deposits from Horváth et al. (2018) including not assessed. From www.hystories.eu/map

Caverns design was then adapted to each of the bedded salt deposits or salt domes. Parameters have been chosen to be consistent with Hystories' Conceptual Design of caverns (D7.1-1 and D7.2-1 reports) and when possible, with Caglayan *et al*. (2020)'s work (Table 4). Most notable similarities are that in domal salt deposits, large caverns are considered, and that in bedded salt deposits, cavern depths are chosen to be similar[7]. Most notable difference is that Hystories operating pressure range is more conservative but is closer to standard values (cf. Bérest *et al*. 2019 for the maximum pressure).

Table 4: Comparison of main salt cavern design hypothesis used in the public capacity estimation works and the Cost model by Hystories WP7

	Caglayan *et al*. 2020	Hystories Work Package 7
Pressure Range	24 % to 80 % of the lithostatic pressure i.e. 0.06 to 0.2 bar/m gradient for a 2500 kg/m^3 overburden	0.06 to 0.18 bar/m pressure gradients (cf. D7.1-1)
Cavern volume in gas	Bedded salt: 350 000 m^3 Domal salt: 525 000 m^3 (after application of the 70% safety factor)	Bedded salt: 380 000 m^3 (MID case of D7.1-1 & D7.2-1) Domal salt: 815 000 m^3 (LOW case of D7.1-1 & D7.2-1)
Cavern geometry (Diameter D and height h)	Bedded salt: D 84 m, h 120 m; cavern neck unclear Domal salt: D 58 m; h 300 m; cavern neck unclear	Domal salt: D 80 m, h 311 m + 30 m neck = 341 m (cf. D7.1-1, LOW case) Bedded salt: D 80 m, h 155 m + 30 m neck = 185 m (cf. D7.1-1, MID case)
Cavern gas temperature (°C)	$Average{:}\ 15 + 0.025 * (depth - cavernHeight/2)$ Range: unclear	$Average{:}\ 15 + 0.03 * (depth - cavernHeight/2)$ Range: 20 °C
Depth	Domal salt: 1400 m for domal salt, in any dome Site-specific for Bedded salt.	Domal salt: 1000 m for domal salt, in any dome (same as D7.1-1) Bedded salt: Site-specific for Bedded salt, cf. table 5.

The cost of developing new salt caverns per deposits given in Hystories and the capacity estimates per country from Caglayan *et al*. (2020) are therefore essentially consistent. We note that these approaches are very high-level estimations. The main limitations are that information are deposit-specific, not site specific. Variation in depth, thickness or salt quality within the deposit are not captured, and water availability or brine disposal possibilities are not assessed. However, this high-level approach can be applied homogeneously though all European salt deposits as shown in Table 5 and is believed to provide consistent overall results and to be the best applicable method at the European scale.

[7] Personal communication from N. Weber

Table 5: Main salt deposit-specific parameters used for the cost estimation. The Conceptual design values of D7.1-1 are also recalled

Country	Ref.	Deposit name	Brief description of the basis for cost estimation (cf. details in D7.1-1)	LCC depth	Cushion / Total Gas	Operating Pressures Max	Operating Pressures Min
				m		bar	bar
D7.1-1 Conceptual Design	LOW		4 caverns of 815 000 m^3 in gas	1000	47 %	180	70
	MID		8 caverns of 380 000 m^3 in gas	1000	43 %	180	70
	HIGH		16 caverns of 185 000 m^3 in gas	1000	41 %	180	70
France	Bed. 1	Alsace Basin	8 caverns of 380 000 m^3 in gas	950	43 %	171	67
	Bed. 2	Bresse Basin		1600	42 %	288	112
	Bed. 3	Greoux Basin		1600	42 %	288	112
	Bed. 4	Valence Basin		1430	42 %	257	100
Germany	Bed. 5	Lower Rhine Basin		1200	43 %	216	84
	Bed. 6	Hessen Werra Basin		900	44 %	162	63
	Bed. 7	Sub-Hercynian Basin		900	44 %	162	63
	Bed. 8	Lausitz Basin		1800	42 %	324	126
Poland	Bed. 9	Leba Salt		1000	43 %	180	70
	Bed. 10	Fore-Sudetic Monocline		1800	42 %	324	126
	Bed. 11	Carpathian Foredeep		1800	42 %	324	126
	Bed. 12	Lublin Trough		1800	42 %	324	126
Romania	Bed. 13	Ocnele Mari		500	47 %	90	35
Spain	Bed. 14	Cardona Saline Formation		1000	43 %	180	70
United Kingdom	Bed. 16	Cheshire Basin		510	47 %	92	36
	Bed. 17	Permian Zechstein Basin		1630	42 %	293	114
	Bed. 18	Larne Salt Field		850	44 %	153	60
	Bed. 19	Wessex Basin		1300	43 %	234	91
BG, PT, ES, NL, DE, DK, EL, UA, PL	Domal salt	Any dome	4 caverns of 815 000 m^3 in gas	1000	47 %	180	70

3.5. Assumptions used for the application of the LCOS to porous media traps

The storages in porous media are essentially following the Conceptual Design defined in D7.1-1. Still, to apply the cost model to each trap, the following assumptions have been made.

Well flowrates are estimated based on the average permeability of synthetic models developed in D2.2-1 as a function of natural gas experience.

- Sites with permeability greater than 100 mD, wells can easily produce 1 MM Sm^3/d
- Sites with permeability between 50-100 mD, wells can produce around 0.5 MM Sm^3/d
- Sites with permeability between 10-50 mD, wells can produce around 0.25 MM Sm^3/d
- Sites with permeability between 1-10 mD, wells can produce around 0.1 MM Sm^3/d.

These estimates of well flowrates will constrain the number of wells required to meet the withdrawal rate. For all porous media traps (underground storages of natural gas, depleted oil & gas fields and deep saline aquifers) it is assumed that new wells are required to handle hydrogen. Due to limits of the conceptual design, only green-field development of storages will be considered, as detailed in section 3.3.

The number of observation wells is assumed to be one fourth of the number of operational wells for all on the type of storage traps.

For depleted gas field and natural gas underground storage, part of the cushion gas will be natural gas. Without any field reference, it is assumed that about half of the cushion gas will be hydrogen. Based upon D2.2-1, the cushion gas to total gas will then be assumed as describe in Table 6:

Table 6: Average ratio for hydrogen cushion gas (CG) to capacity (TG) for the main storage categories from D2.2-1

	CG/TG
Underground Gas Storage	0.53/2=0.265
Depleted Gas Field	0.62
Deep Saline Aquifer	0.56
Depleted Oil Field	0.52

3.6. Results of the LCOS for the Operating Cycle 1 (seasonal)

3.6.1. EU-27+UK+Ukraine results

The levelized cost of storage obtained for both porous media and salt caverns is presented in the figure below:

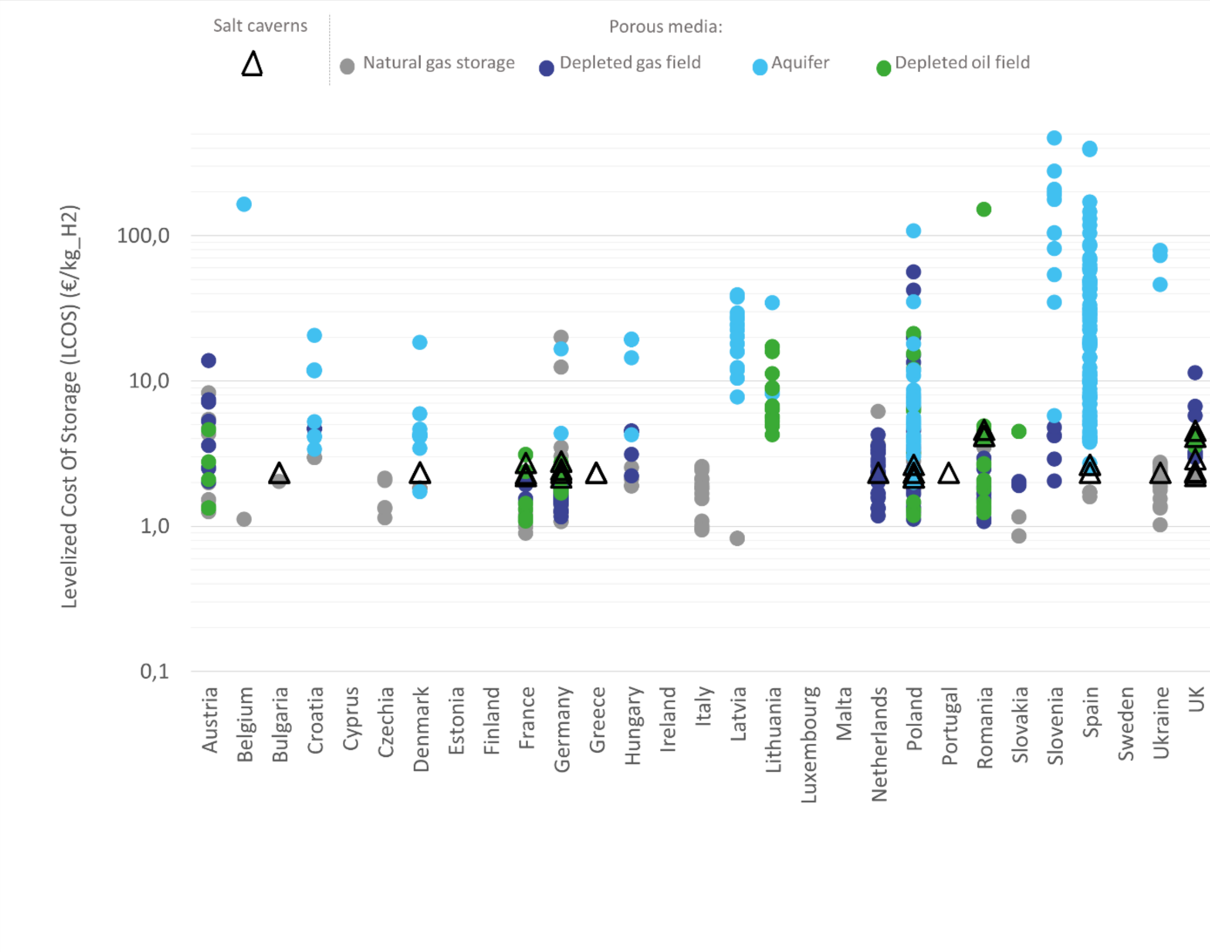


Figure 6: LCOS for porous media and salt caverns, Operating Cycle 1 (seasonal), per country

This logarithm scale shows the large range of the costs that have been found, especially for porous media. This reflects the diversity of the geological conditions that introduced in the WP1 trap database. High costs are also due to the small capacity of part of the traps found in the database, when compared to a typical underground storage site capacity.

Cost of salt cavern are more concentrated, reflecting both that there are less data points, that salt deposit in untypical conditions were not selected, and that typical size (from the Conceptual Design D7.1) are considered here since none of the considered salt deposits is limiting a project to be smaller.

In order to consider the cost of developing smaller projects in salt cavern, the cost model has also been applied to salt cavern projects of smaller capacity, down to 1/8th of the Conceptual Design capacity of 250 MM Sm^3. This enables a comparison with porous media traps of the same capacity.

The capacity of the storage has a major influence on the cost result. It is introduced in Figure 7. For porous media, each dot is the maximal size of the storage project that can be developed on that trap. For salt caverns, there is no clear maximum to the size of a project at a given location (for each country having suitable salt, the technical capacity in salt is larger than the maximal demand for that country). The cost of storage is therefore represented as a solid line.

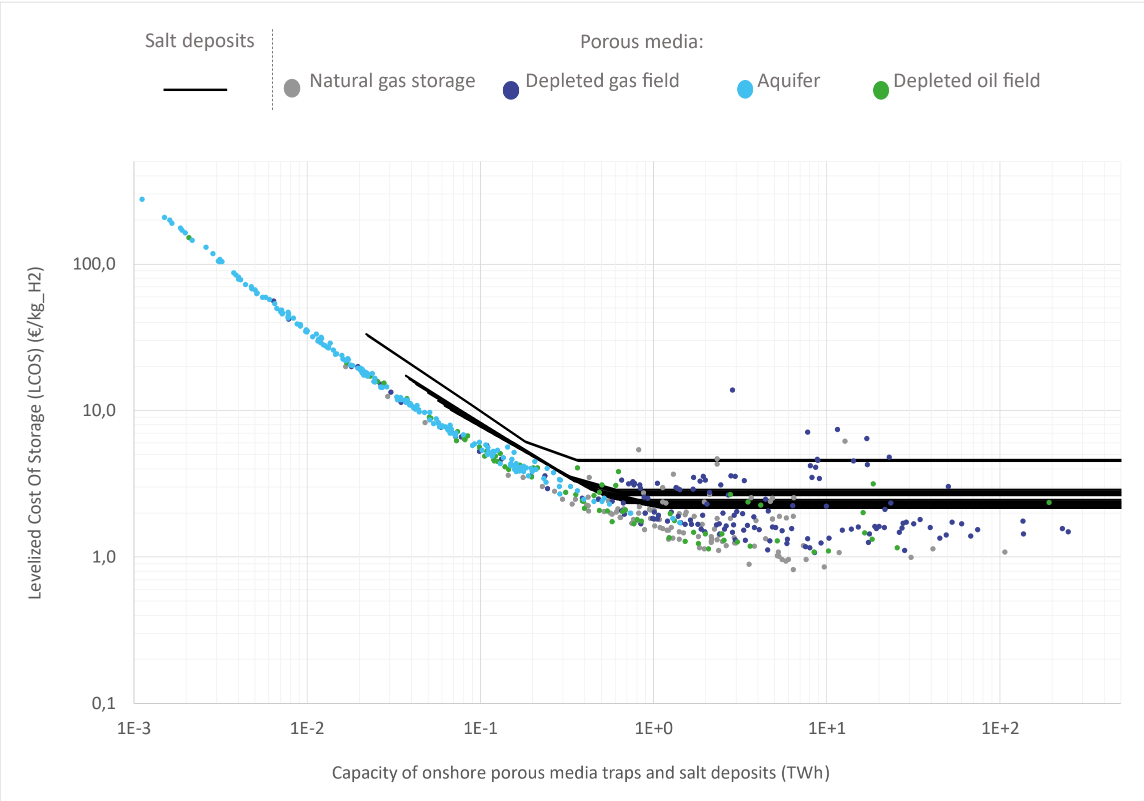
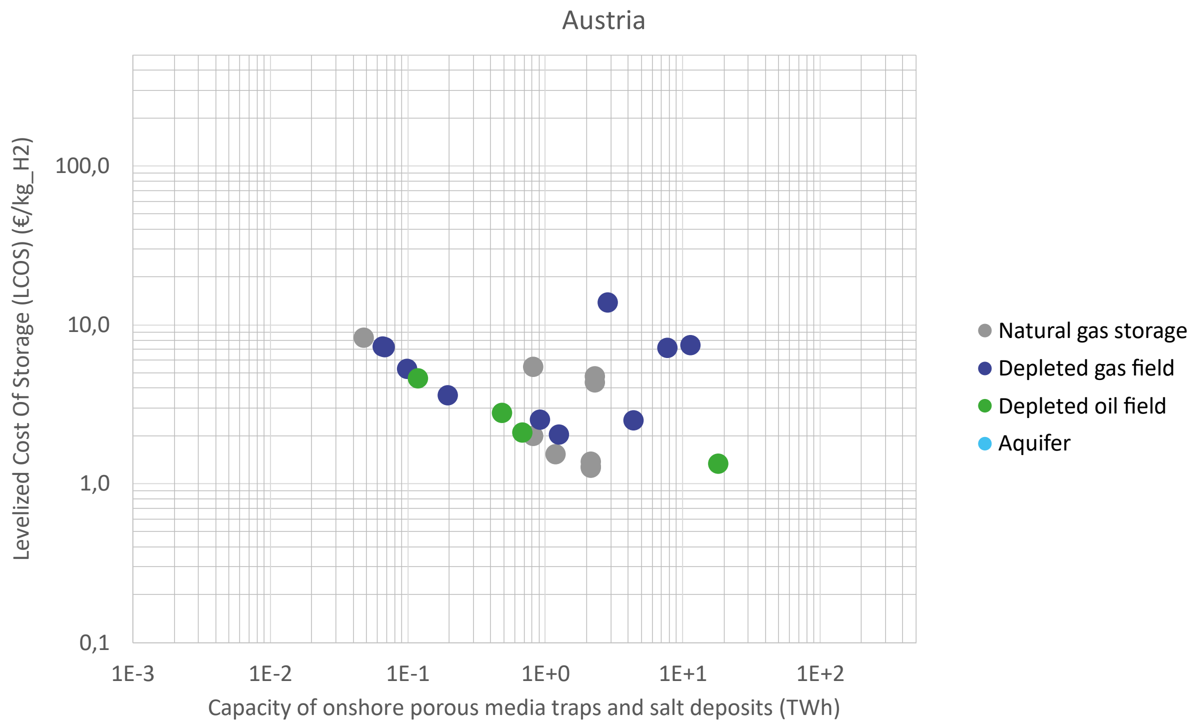


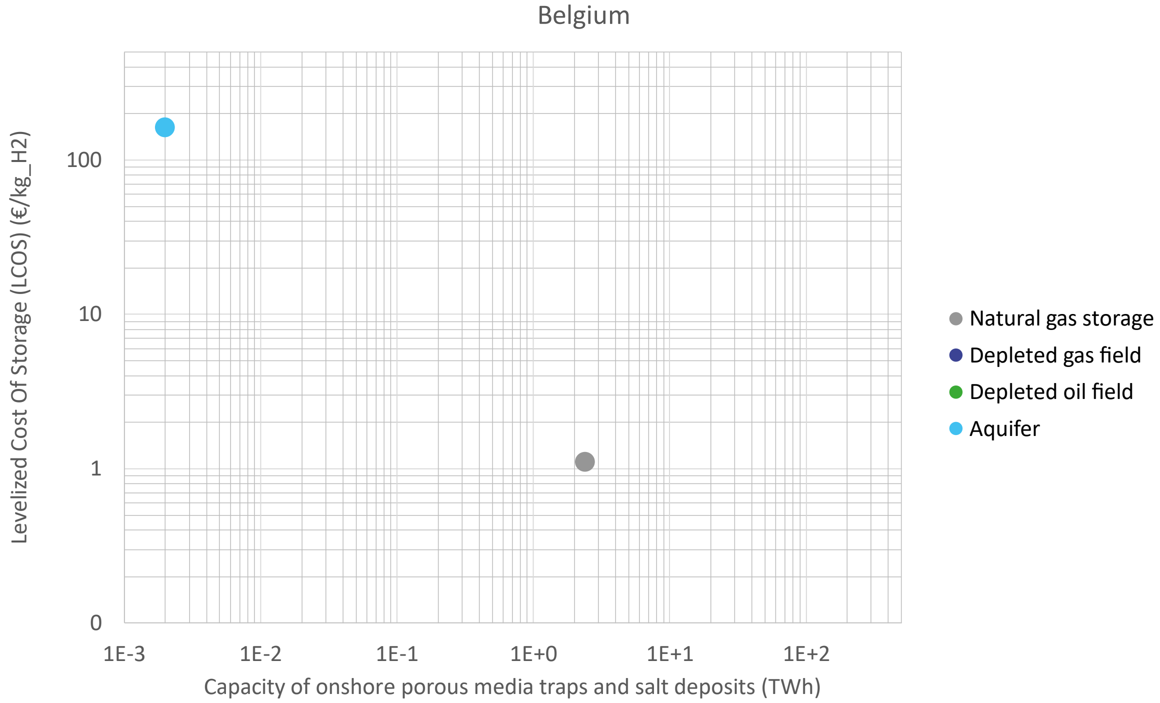
Figure 7: LCOS for onshore porous media and salt caverns in EU-27+UK+Ukraine, Operating Cycle 1 (seasonal) per capacity
For porous media (dots indicate the maximum capacity of the trap) and
for salt caverns (size to be chosen by design on the solid line)

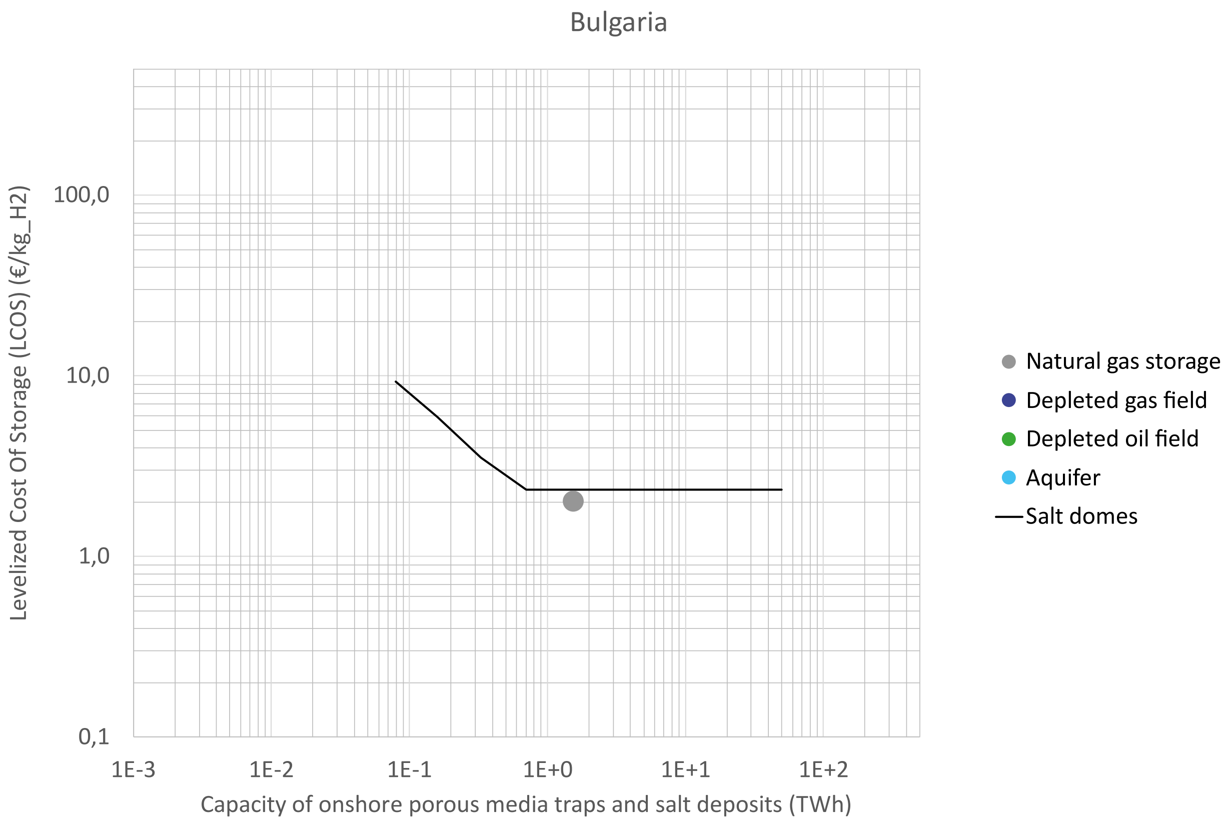
We note that these costs are based on the application of D7.2 parametric model able to adapt to most of the relevant parameters, but it is still far from a specific feasibility and cost estimation study on a given site. Significant costs optimizations or increases could be found, notably with site specificities differ largely from the conceptual design cases from D7.1 (for instance, very low capacity sites).

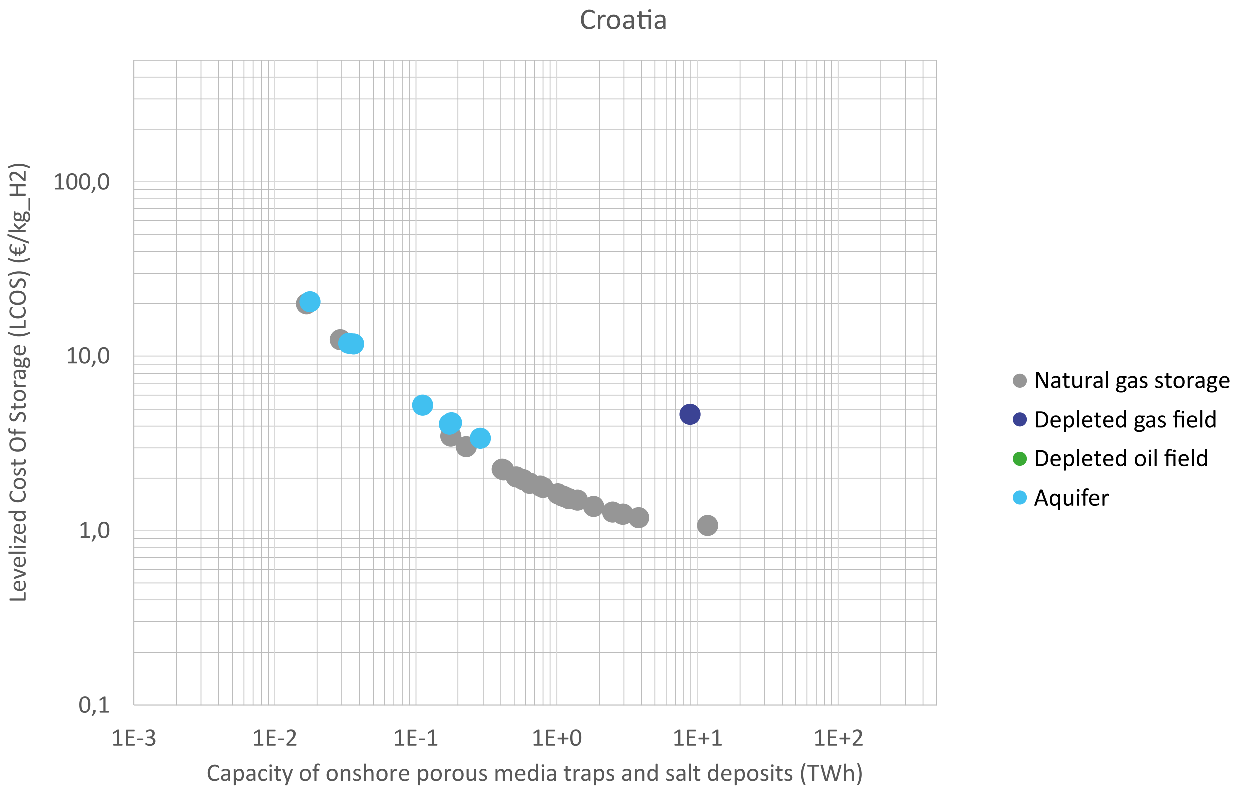
3.6.2. Country-specific results

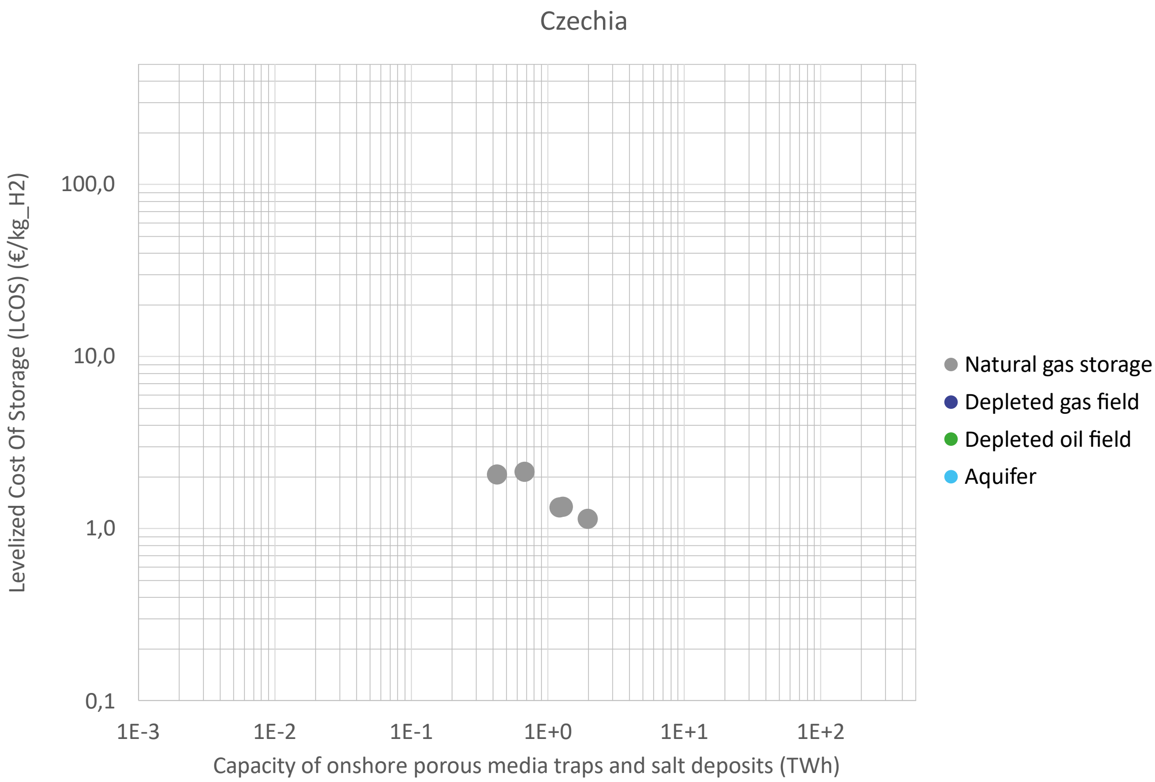
In the above section, LCOS are given per country without the influence of the capacity (Figure 6) and per capacity without mentioning the country (Figure 7). Including both metrics is difficult at European level. It is done below in Figure 8 for each country.

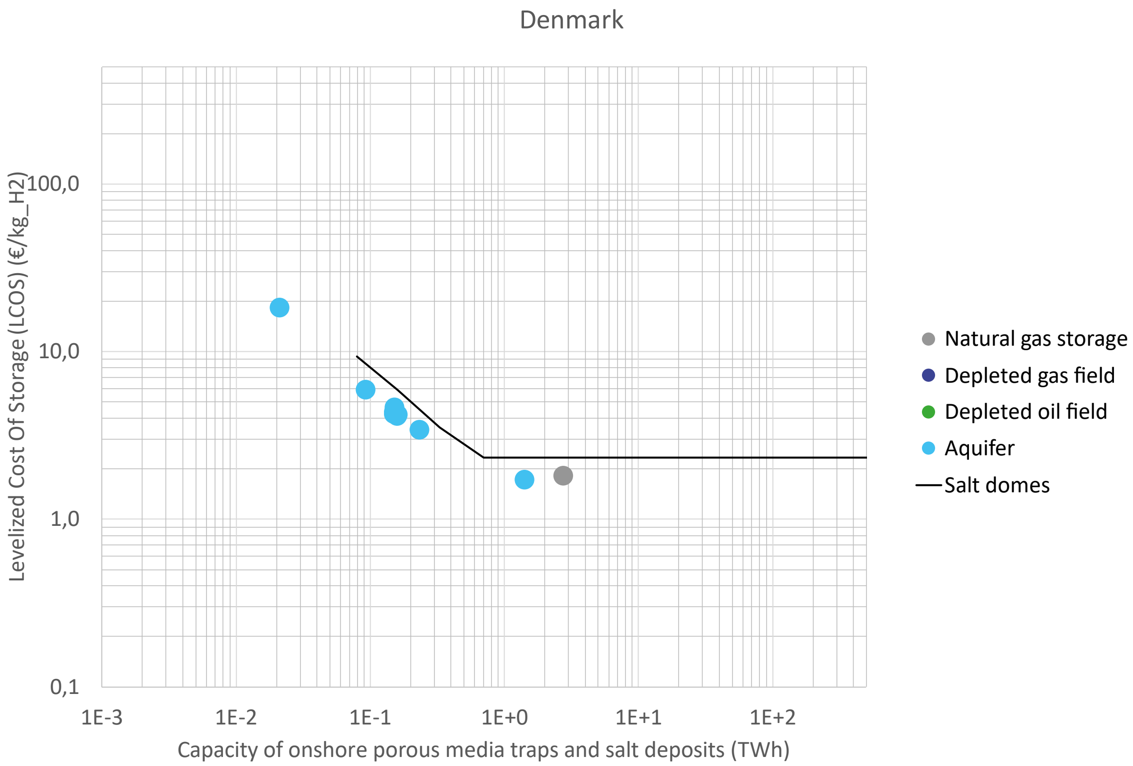


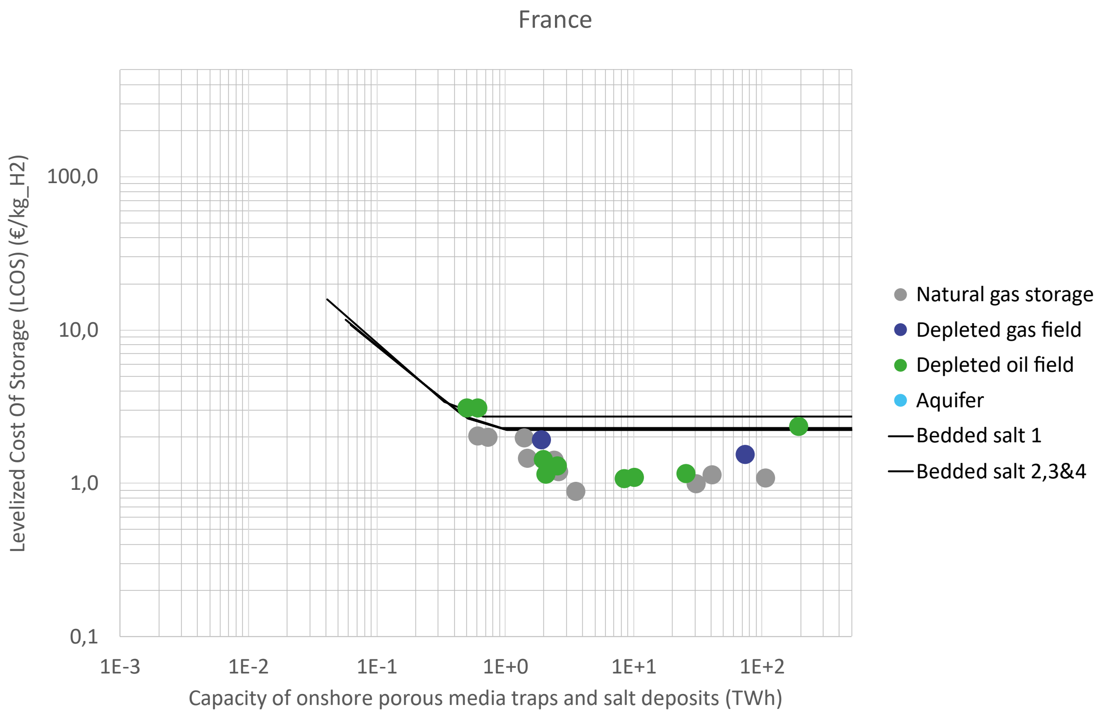



Bulgaria
Levelized Cost Of Storage (LCOS) (€/kg_H2)
100,0
10,0
1,0
0,1
1E-3
1E-2
1E-1
1E+0
1E+1
1E+2
Capacity of onshore porous media traps and salt deposits (TWh)
Natural gas storage
Depleted gas field
Depleted oil field
Aquifer
Salt domes


Croatia
Levelized Cost Of Storage (LCOS) (€/kg_H2)
100,0
10,0
1,0
0,1
1E-3
1E-2
1E-1
1E+0
1E+1
1E+2
Capacity of onshore porous media traps and salt deposits (TWh)
Natural gas storage
Depleted gas field
Depleted oil field
Aquifer


Czechia
Levelized Cost Of Storage (LCOS) (€/kg_H2)
100,0
10,0
1,0
0,1
1E-3
1E-2
1E-1
1E+0
1E+1
1E+2
Capacity of onshore porous media traps and salt deposits (TWh)
Natural gas storage
Depleted gas field
Depleted oil field
Aquifer


Denmark
Levelized Cost Of Storage (LCOS) (€/kg_H2)
100,0
10,0
1,0
0,1
1E-3
1E-2
1E-1
1E+0
1E+1
1E+2
Capacity of onshore porous media traps and salt deposits (TWh)
Natural gas storage
Depleted gas field
Depleted oil field
Aquifer
Salt domes


France
Levelized Cost Of Storage (LCOS) (€/kg_H2)
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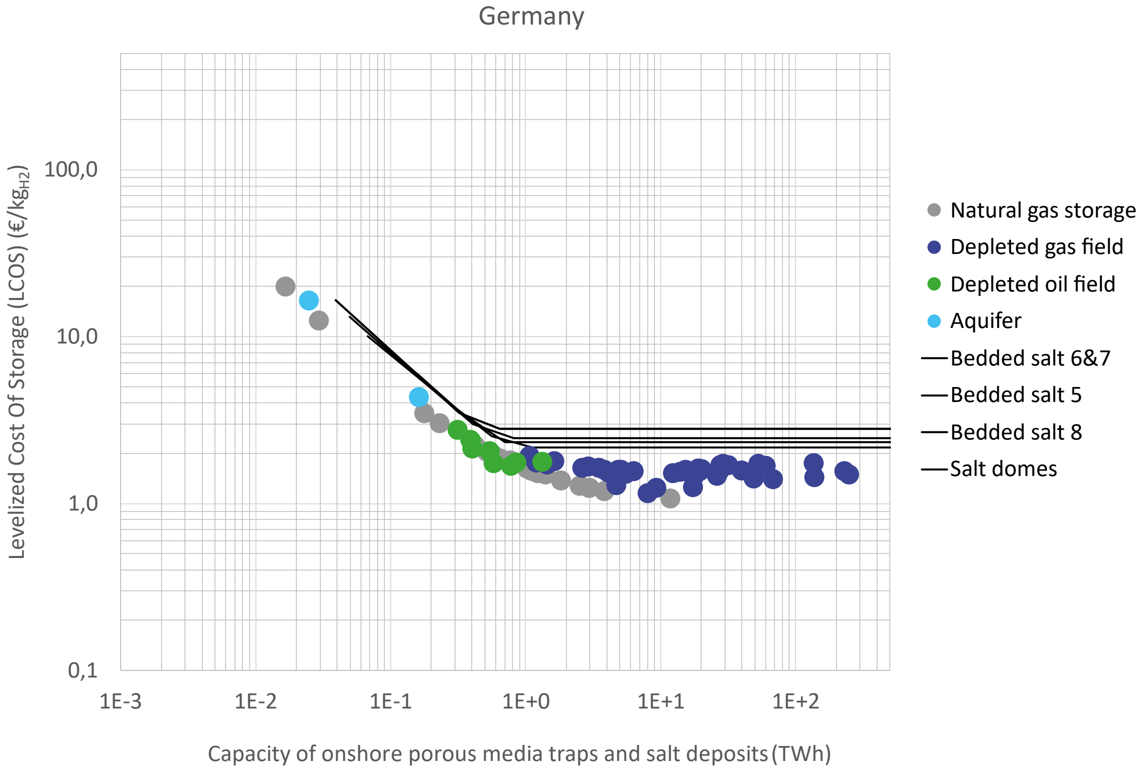
10,0
1,0
0,1
1E-3
1E-2
1E-1
1E+0
1E+1
1E+2
Capacity of onshore porous media traps and salt deposits (TWh)
Natural gas storage
Depleted gas field
Depleted oil field
Aquifer
Bedded salt 1
Bedded salt 2,3&4


Germany
Levelized Cost Of Storage (LCOS) (€/kg$_{H2}$)
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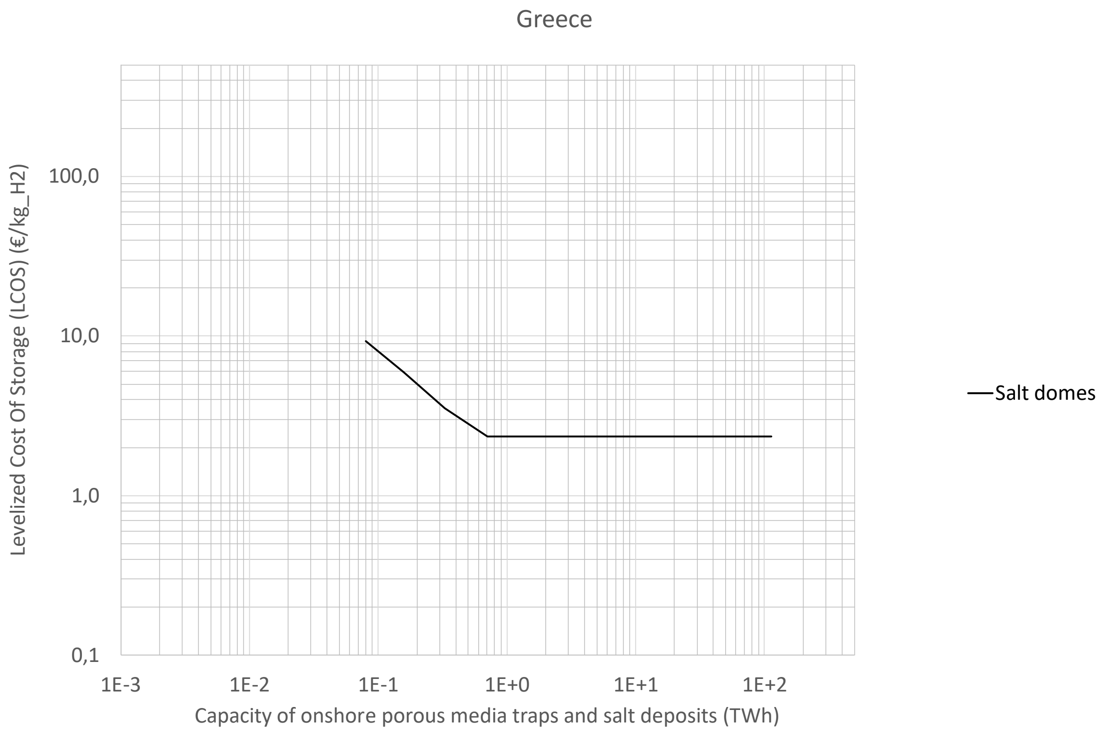
0,1
1E-3
1E-2
1E-1
1E+0
1E+1
1E+2
Capacity of onshore porous media traps and salt deposits (TWh)
Natural gas storage
Depleted gas field
Depleted oil field
Aquifer
Bedded salt 6&7
Bedded salt 5
Bedded salt 8
Salt domes


Greece
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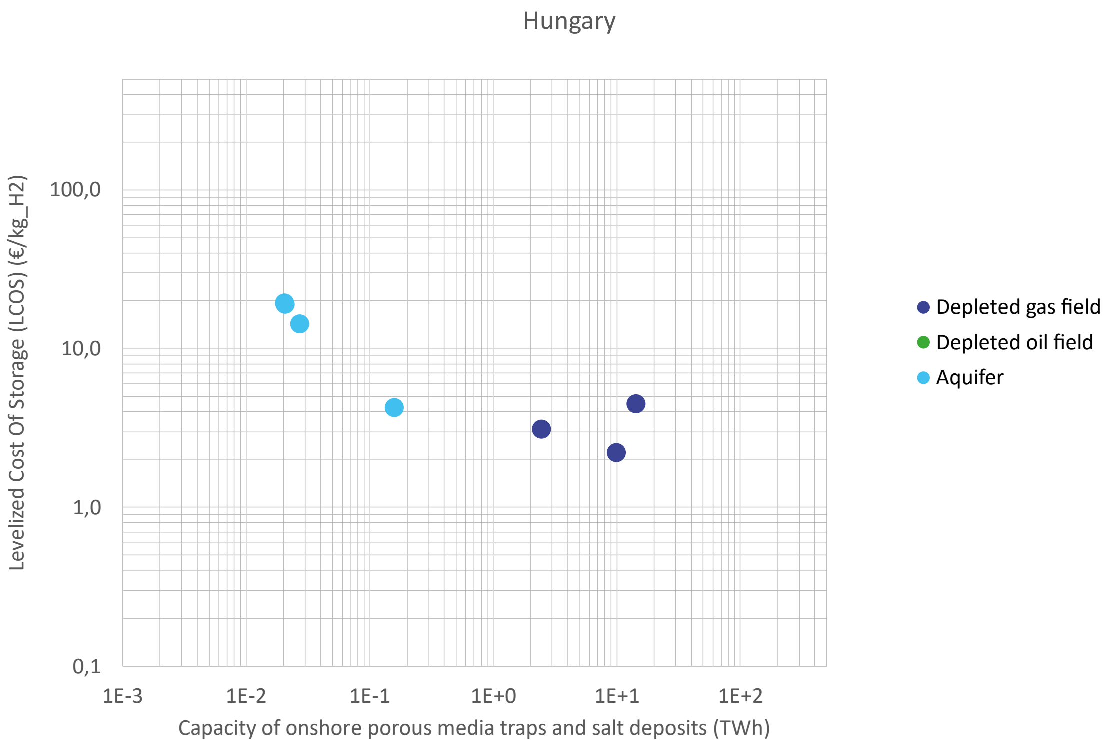
1E-2
1E-1
1E+0
1E+1
1E+2
Levelized Cost Of Storage (LCOS) (€/kg_H2)
Capacity of onshore porous media traps and salt deposits (TWh)
Salt domes


Hungary
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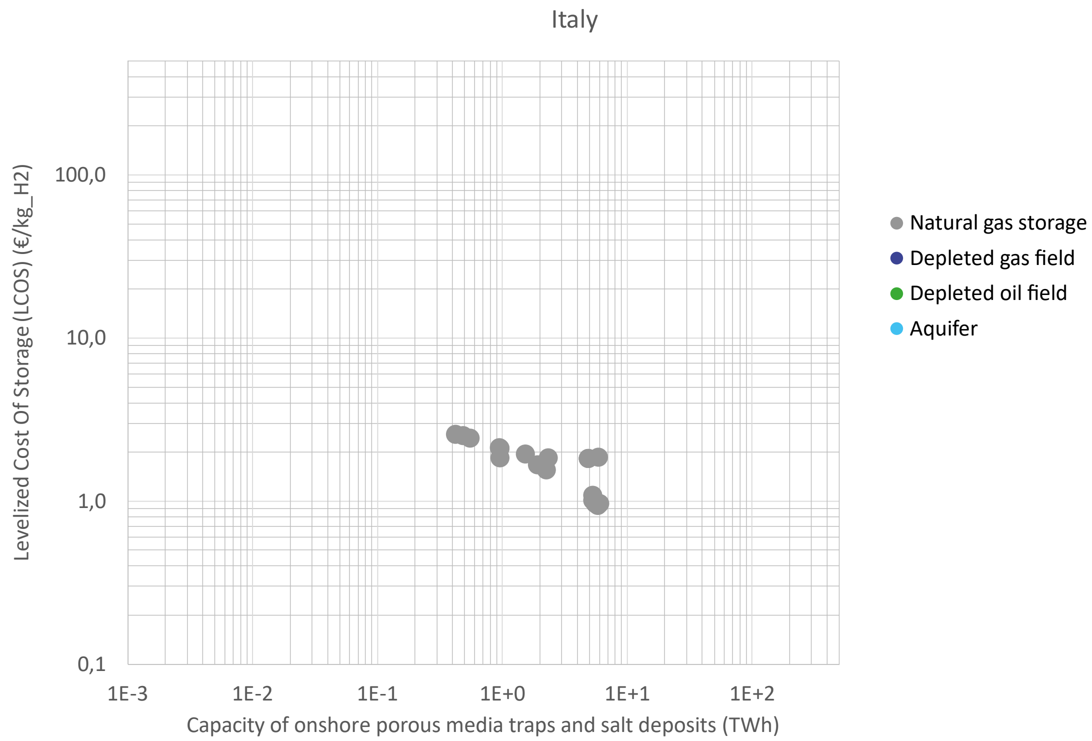
1E-3
1E-2
1E-1
1E+0
1E+1
1E+2
Levelized Cost Of Storage (LCOS) (€/kg_H2)
Capacity of onshore porous media traps and salt deposits (TWh)
Depleted gas field
Depleted oil field
Aquifer


Italy
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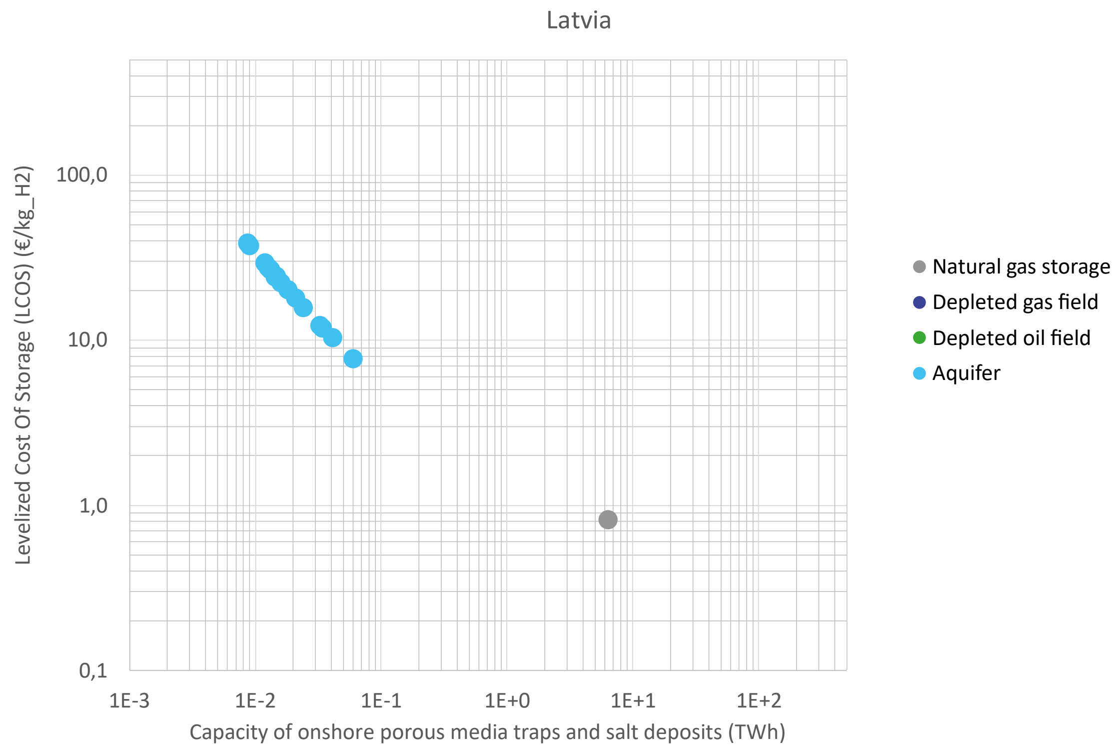
1E-3
1E-2
1E-1
1E+0
1E+1
1E+2
Levelized Cost Of Storage (LCOS) (€/kg_H2)
Capacity of onshore porous media traps and salt deposits (TWh)
Natural gas storage
Depleted gas field
Depleted oil field
Aquifer


Latvia
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1E-3
1E-2
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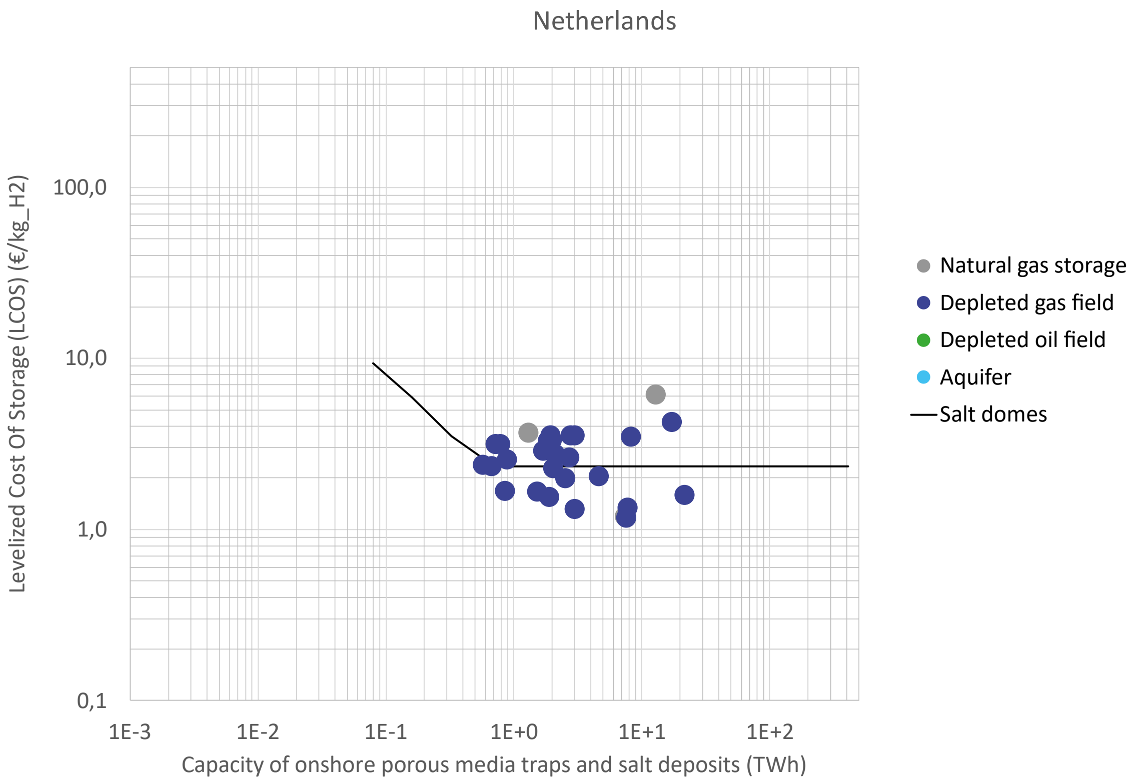
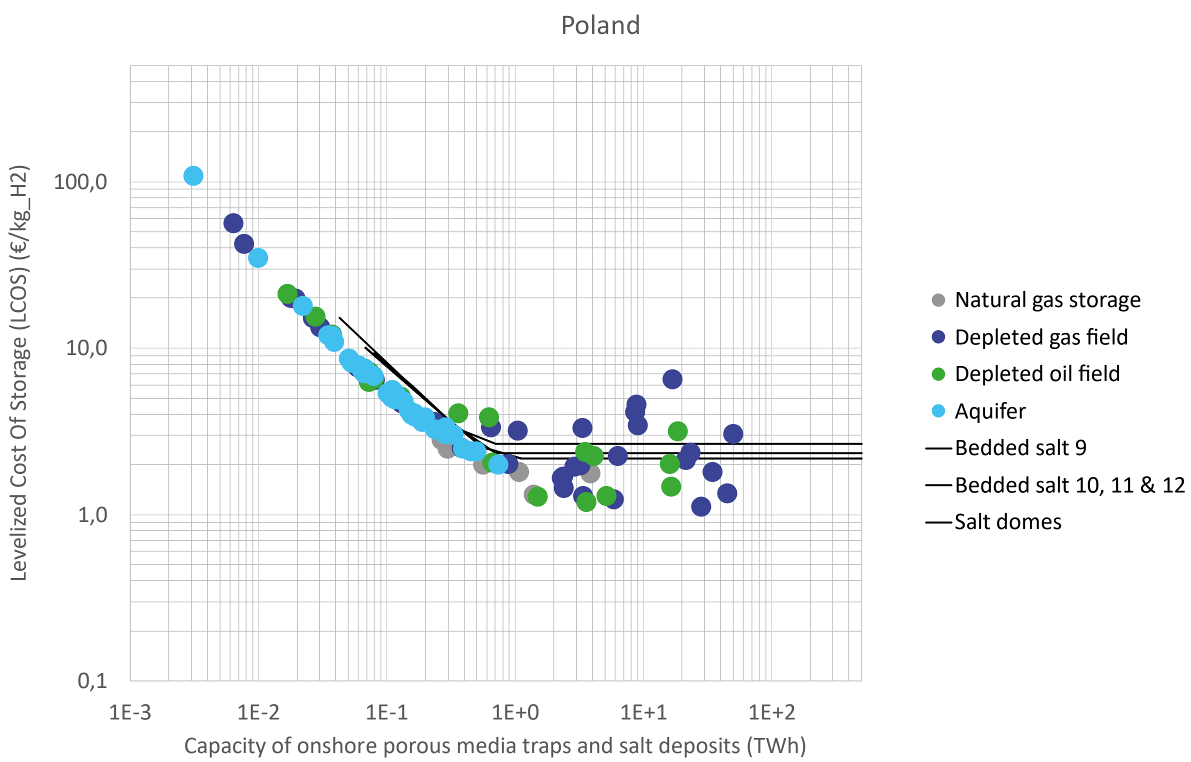
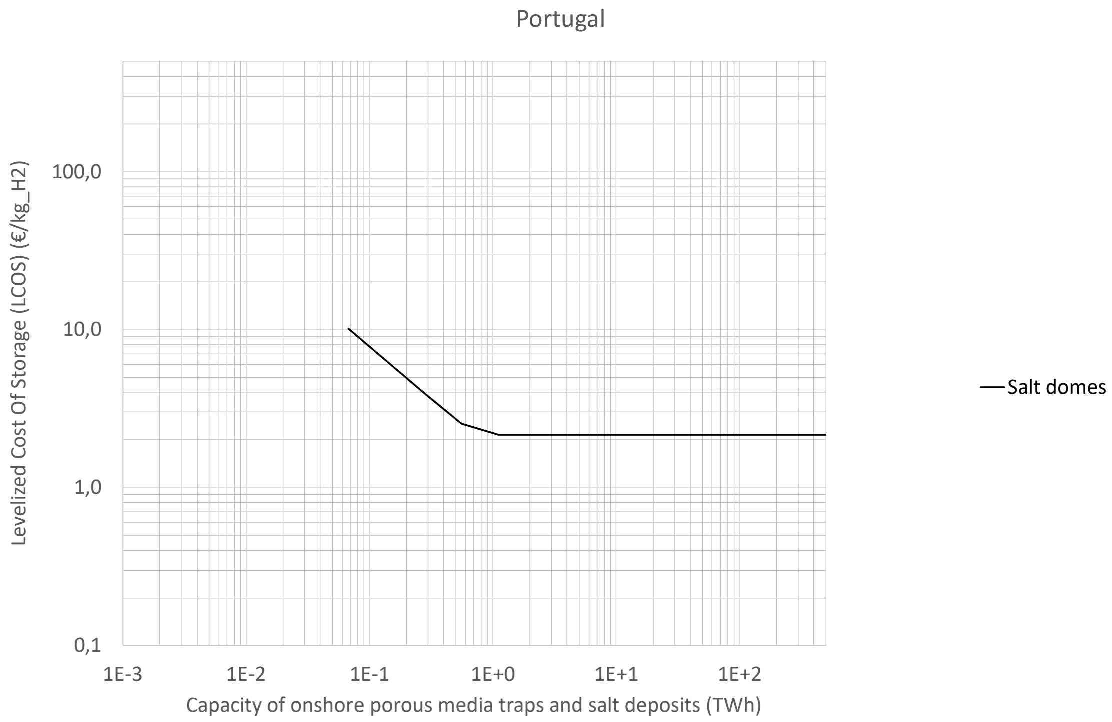
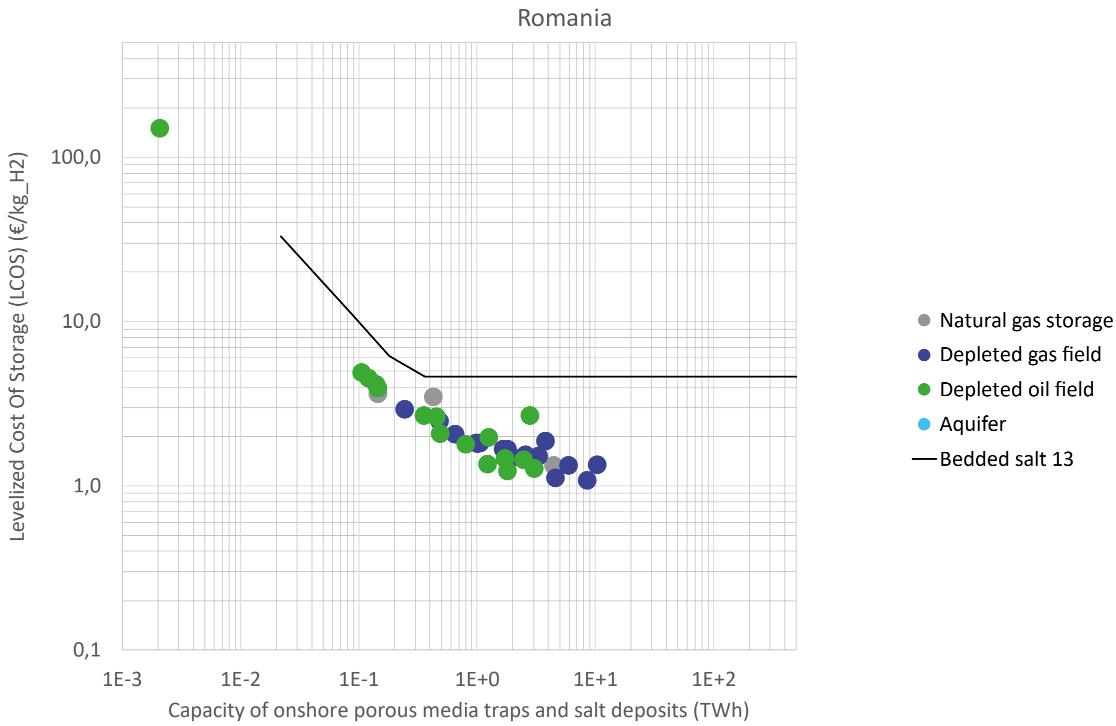
1E+2
Levelized Cost Of Storage (LCOS) (€/kg_H2)
Capacity of onshore porous media traps and salt deposits (TWh)
Natural gas storage
Depleted gas field
Depleted oil field
Aquifer


Netherlands
Levelized Cost Of Storage (LCOS) (€/kg_H2)
100,0
10,0
1,0
0,1
1E-3
1E-2
1E-1
1E+0
1E+1
1E+2
Capacity of onshore porous media traps and salt deposits (TWh)
Natural gas storage
Depleted gas field
Depleted oil field
Aquifer
Salt domes


Poland
Levelized Cost Of Storage (LCOS) (€/kg_H2)
100,0
10,0
1,0
0,1
1E-3
1E-2
1E-1
1E+0
1E+1
1E+2
Capacity of onshore porous media traps and salt deposits (TWh)
Natural gas storage
Depleted gas field
Depleted oil field
Aquifer
Bedded salt 9
Bedded salt 10, 11 & 12
Salt domes



Portugal
100,0
10,0
1,0
0,1
1E-3
1E-2
1E-1
1E+0
1E+1
1E+2
Levelized Cost Of Storage (LCOS) (€/kg_H2)
Capacity of onshore porous media traps and salt deposits (TWh)
Salt domes



Romania
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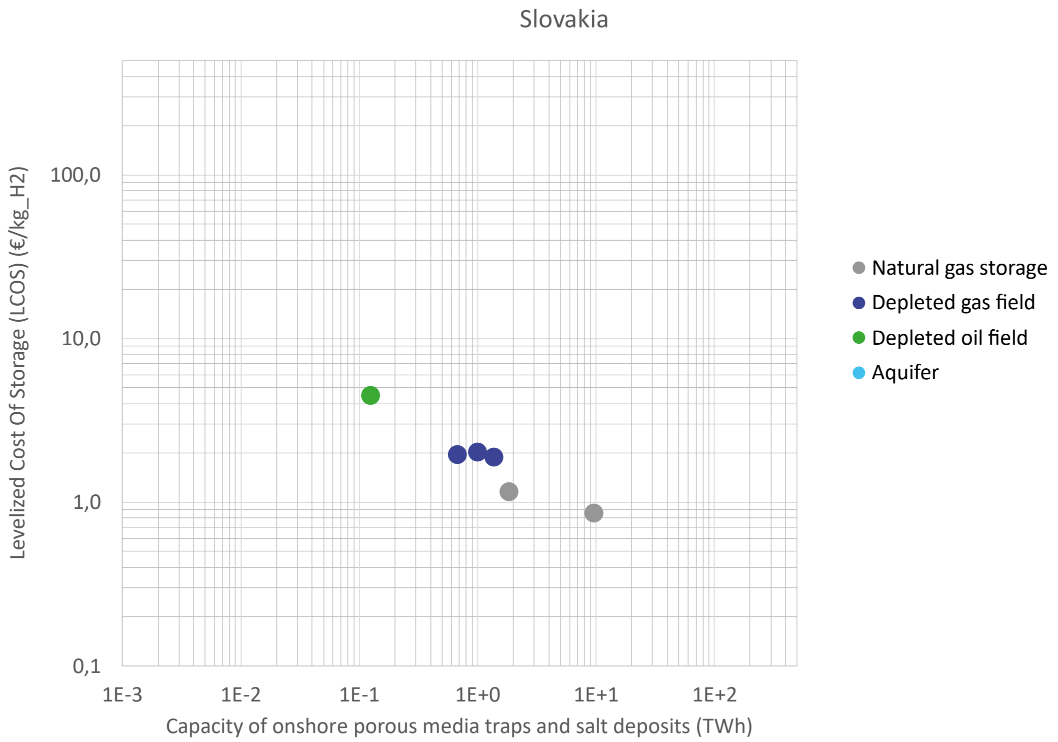
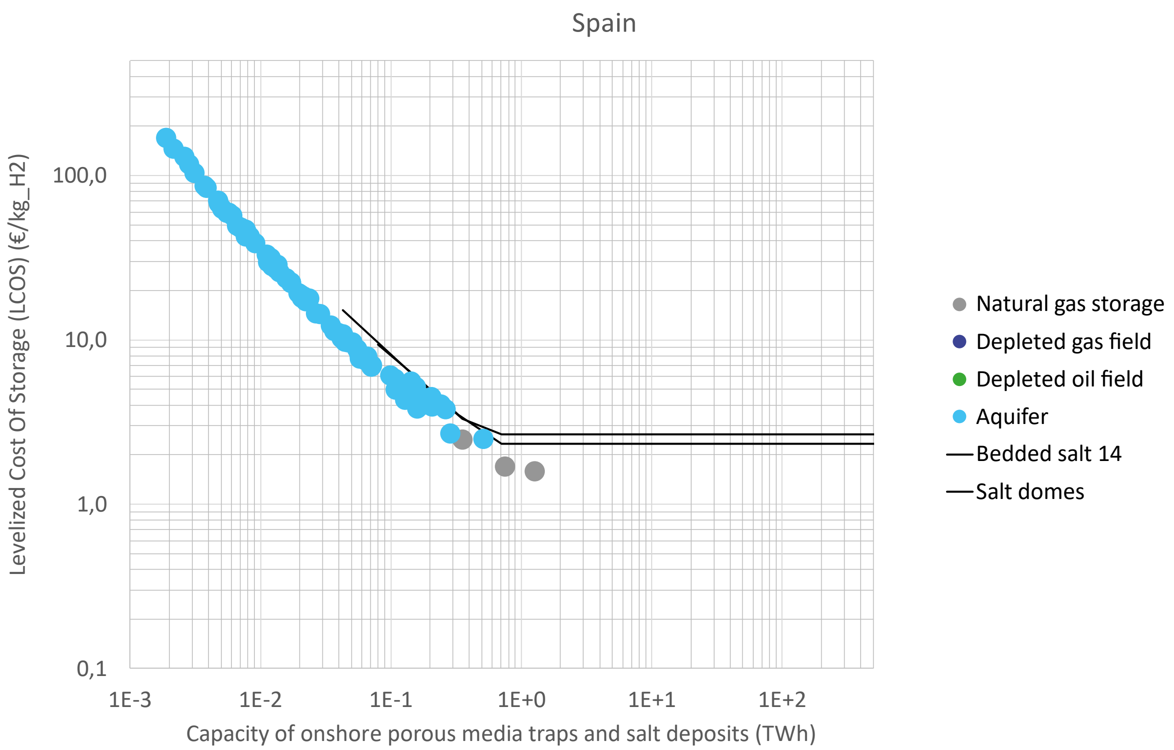
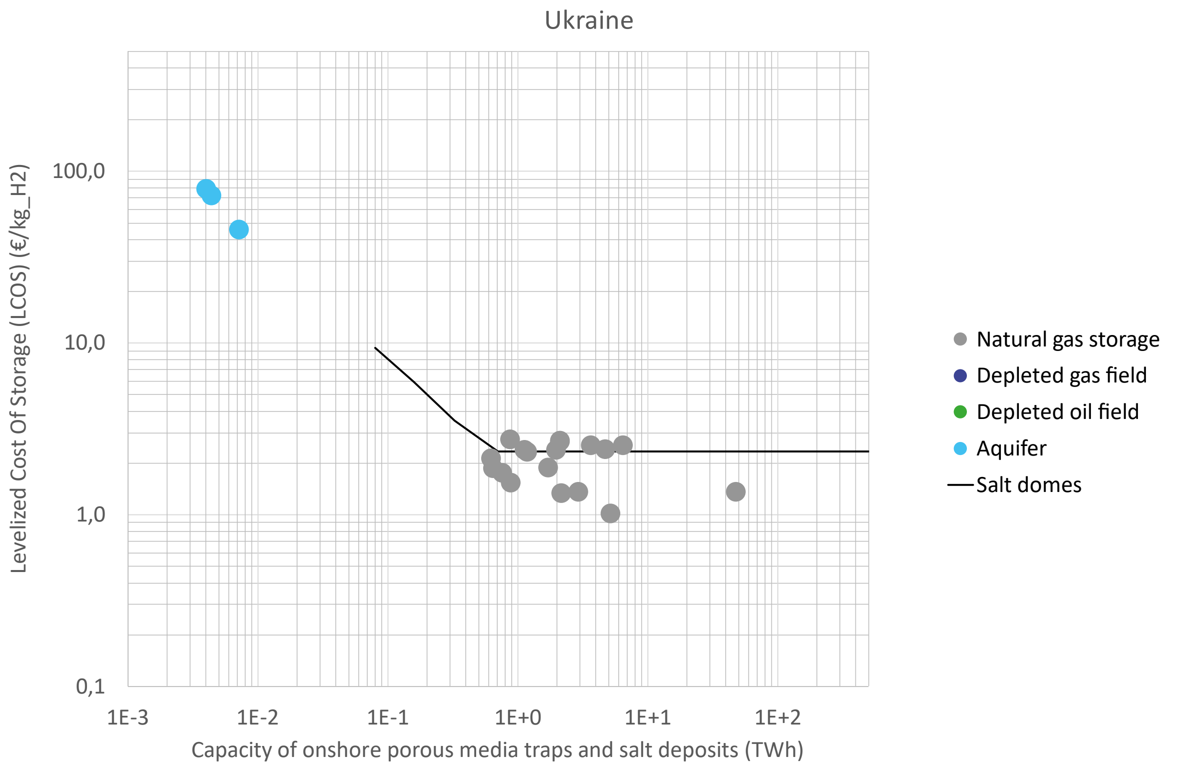
0,1
1E-3
1E-2
1E-1
1E+0
1E+1
1E+2
Levelized Cost Of Storage (LCOS) (€/kg_H2)
Capacity of onshore porous media traps and salt deposits (TWh)
Natural gas storage
Depleted gas field
Depleted oil field
Aquifer
Bedded salt 13


Slovakia
Levelized Cost Of Storage (LCOS) (€/kg_H2)
100,0
10,0
1,0
0,1
1E-3
1E-2
1E-1
1E+0
1E+1
1E+2
Capacity of onshore porous media traps and salt deposits (TWh)
Natural gas storage
Depleted gas field
Depleted oil field
Aquifer


Spain
Levelized Cost Of Storage (LCOS) (€/kg_H2)
100,0
10,0
1,0
0,1
1E-3
1E-2
1E-1
1E+0
1E+1
1E+2
Capacity of onshore porous media traps and salt deposits (TWh)
Natural gas storage
Depleted gas field
Depleted oil field
Aquifer
Bedded salt 14
Salt domes



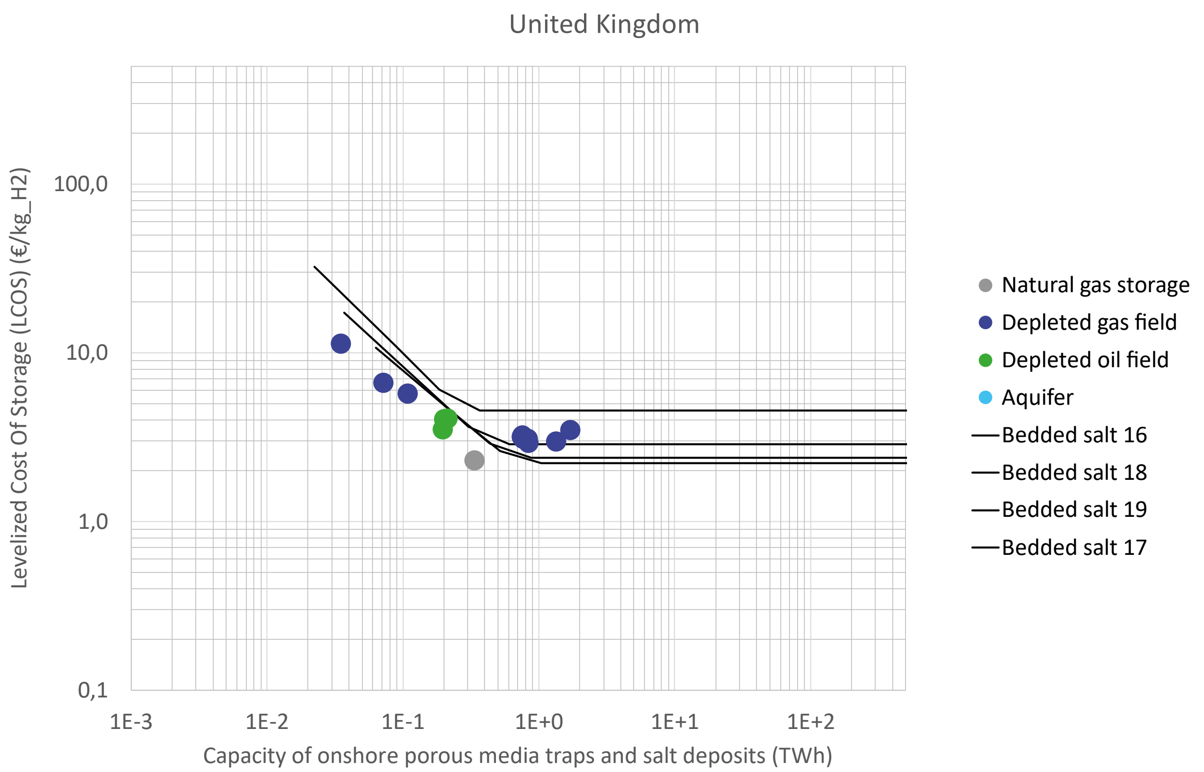


Figure 8: LCOS for onshore porous media and salt caverns per country, Operating Cycle 1 (seasonal) per capacity, for porous media (for the total capacity of the trap) and for salt caverns (capacity to be chosen by design on the solid line). Bedded salt deposit number refers to the Figure 5.

3.7. Results of the LCOS for the Operating Cycle 2 (fast cycle)

3.7.1. EU-27+UK+Ukraine results

The Levelized cost of storage obtained for both porous media and salt caverns is presented in the Figure 9 below:

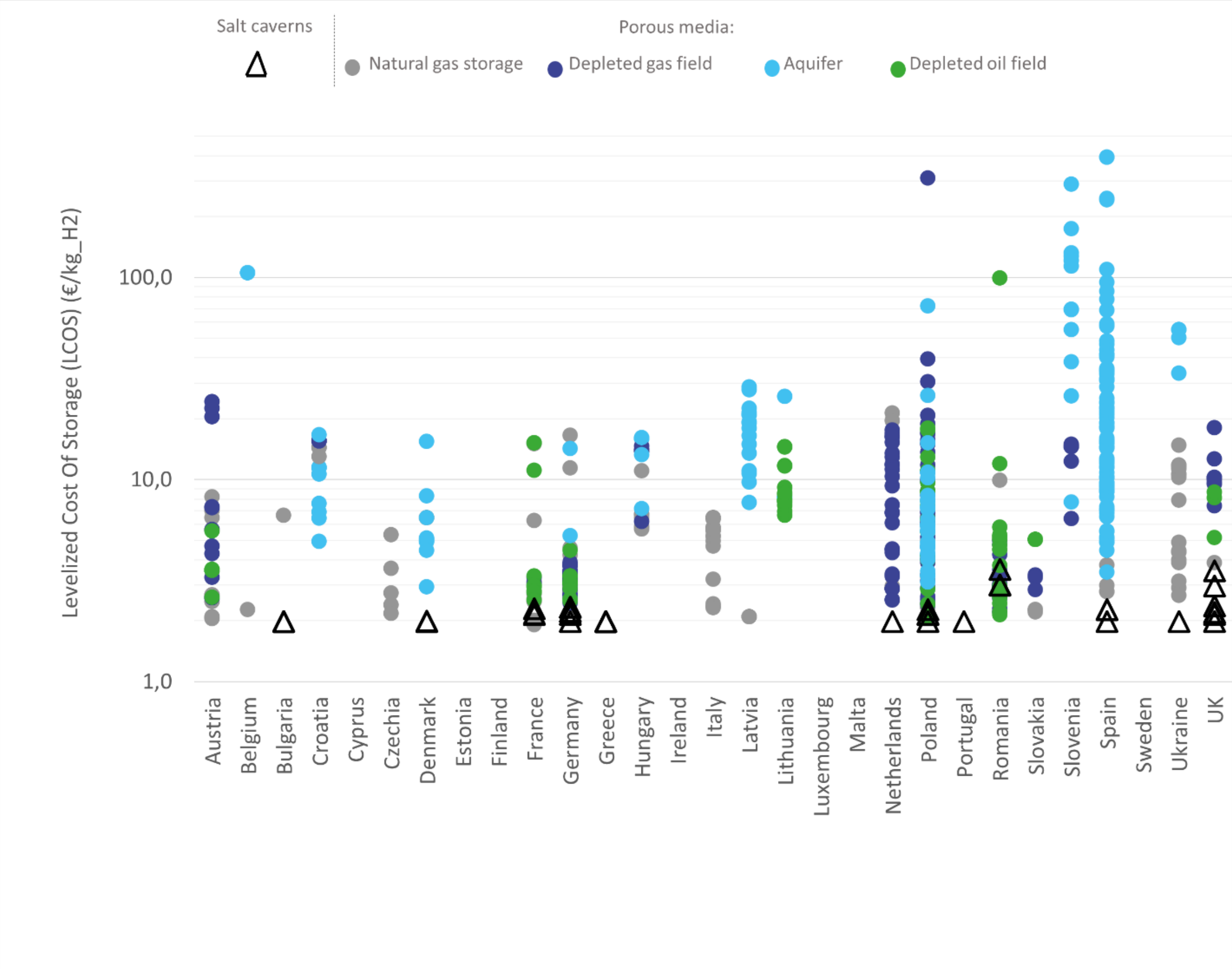


Figure 9: LCOS for porous media and salt caverns, Operating Cycle 2 (fast cycle), per country

As for the seasonal cycle case exposed in the previous section, and for the same reasons (please refer to it), this logarithm scale shows the large diversity of the costs that have been found, especially for porous media. It is therefore interesting to plot the capacity of the potential storage site. It is presented in the Figure 10 below:

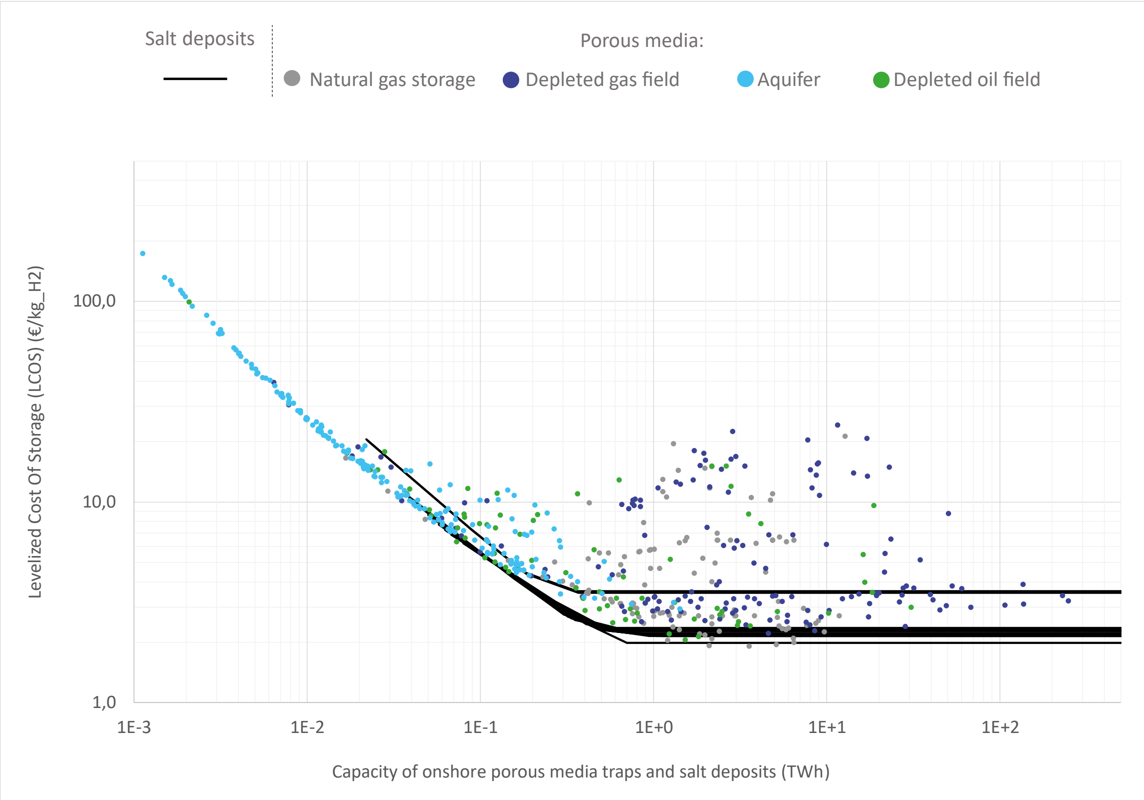


Figure 10: LCOS for onshore porous media and salt caverns in EU-27+UK+Ukraine, Operating Cycle 2 (fast cycle) per capacity, for porous media (for the total capacity of the trap) and for salt caverns (size to be chosen by design on the solid line)

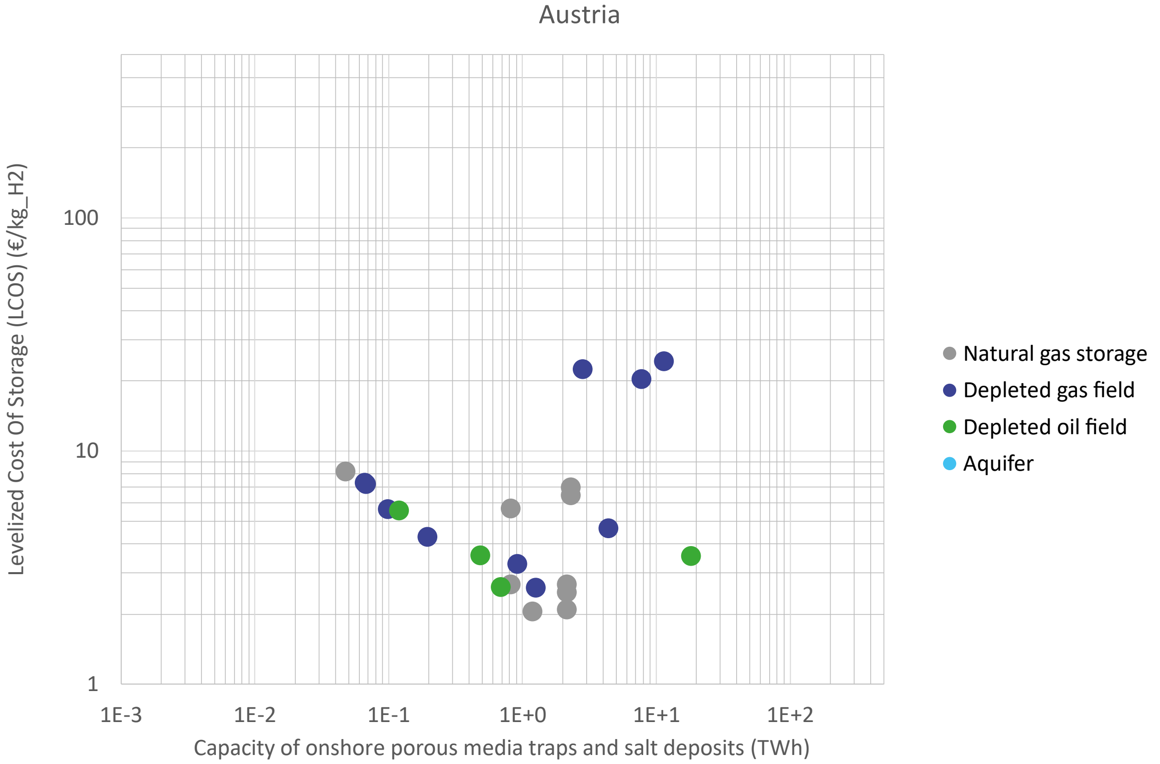
- LCOS for the Operation Cycle 2 (fast cycle) is 2.3 €/kg for salt cavern and 2.7 €/kg for porous storages.

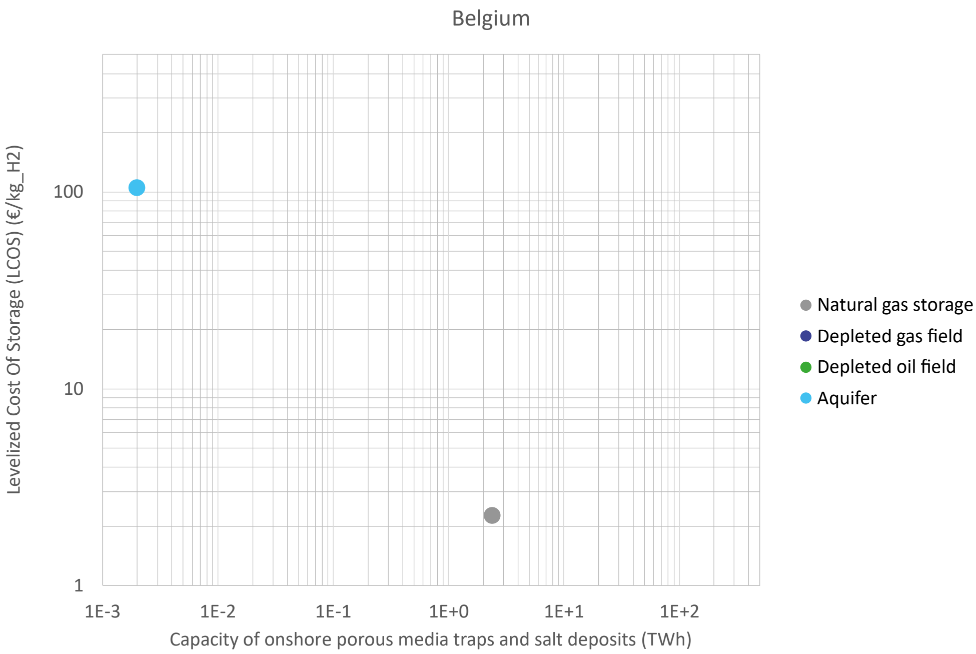
For fast cycles, salt caverns are among the cost-effective option. We however note that there are a few porous media traps for which storage development cost could be lower than for the salt deposits, and significantly lower than the LCOS found for the Conceptual Design (2.7 €/kg). In these traps:

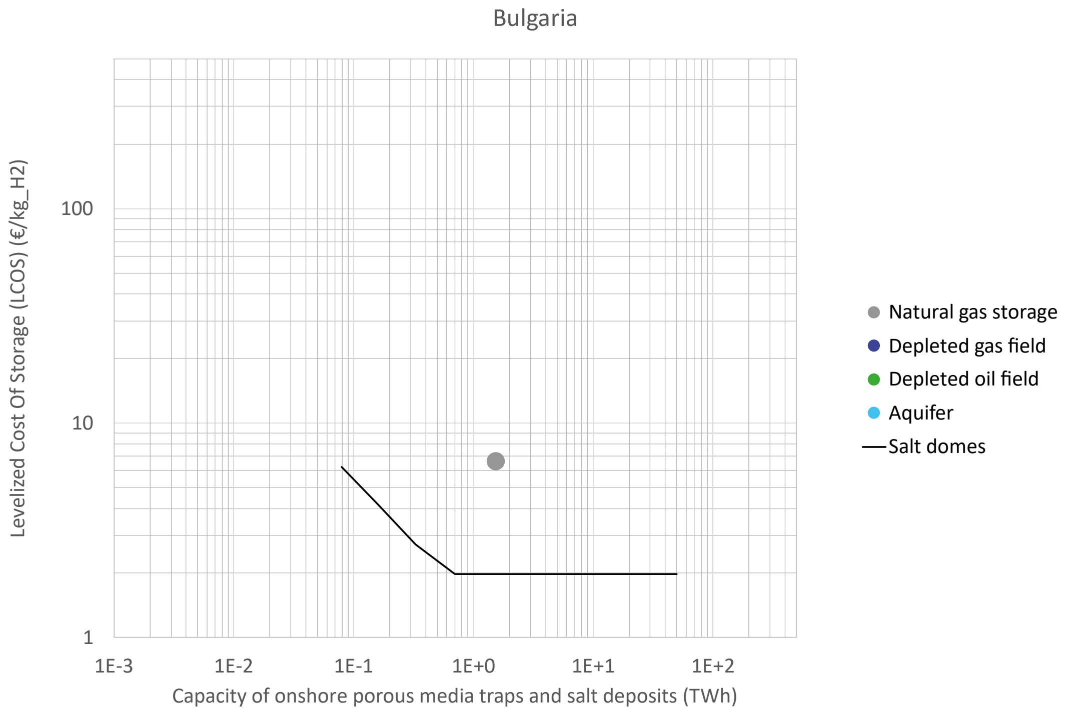
- high flow rates can be achieved without a particularly high number of wells.
- a large storage capacity can be obtained even with a limited maximum pressure. This enables limited compression costs.

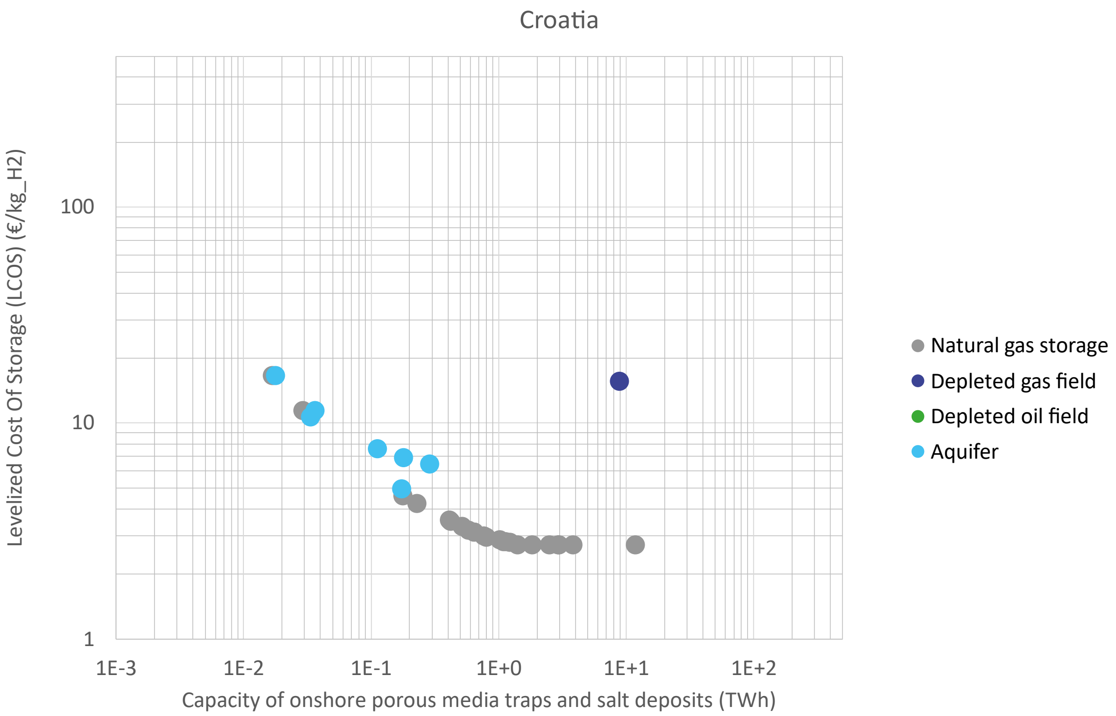
3.7.2. Country-specific results

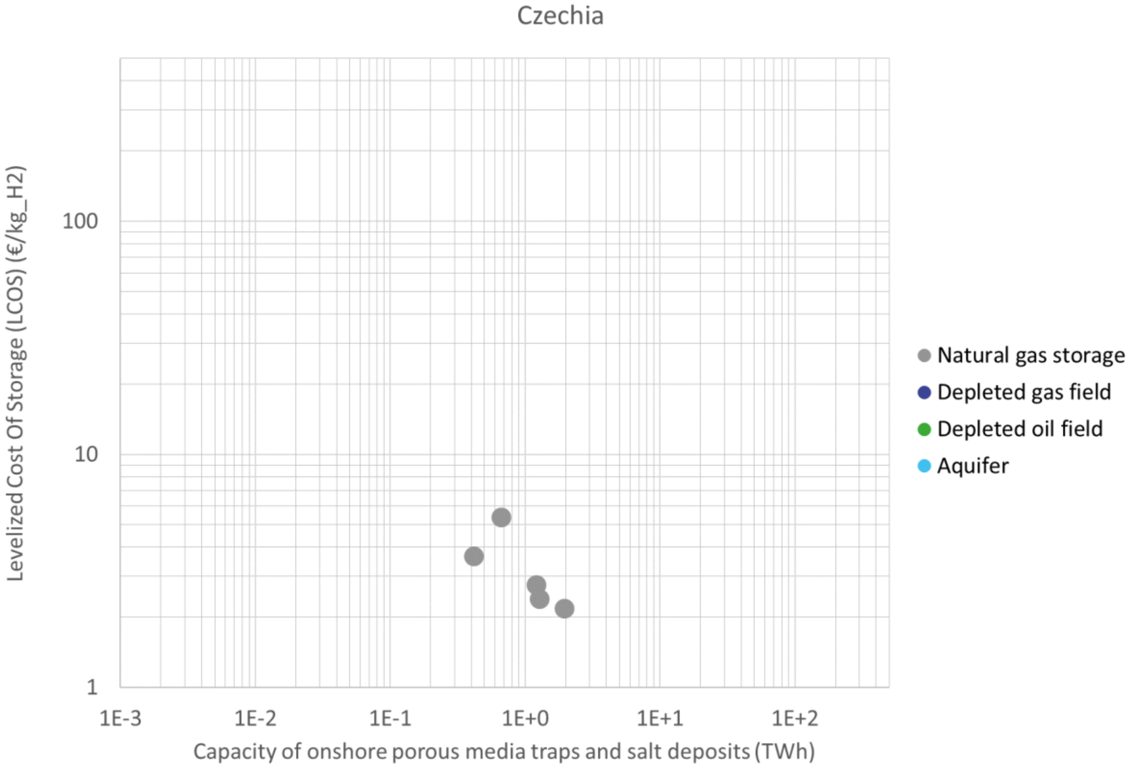
In the above section, LCOS are given per country without the influence of the capacity (Figure 9) and per capacity without mentioning the country (Figure 10). Including both information is difficult at European level. It is done below for each country (Figure 11) where storage in porous media and/or salt cavern is feasible.

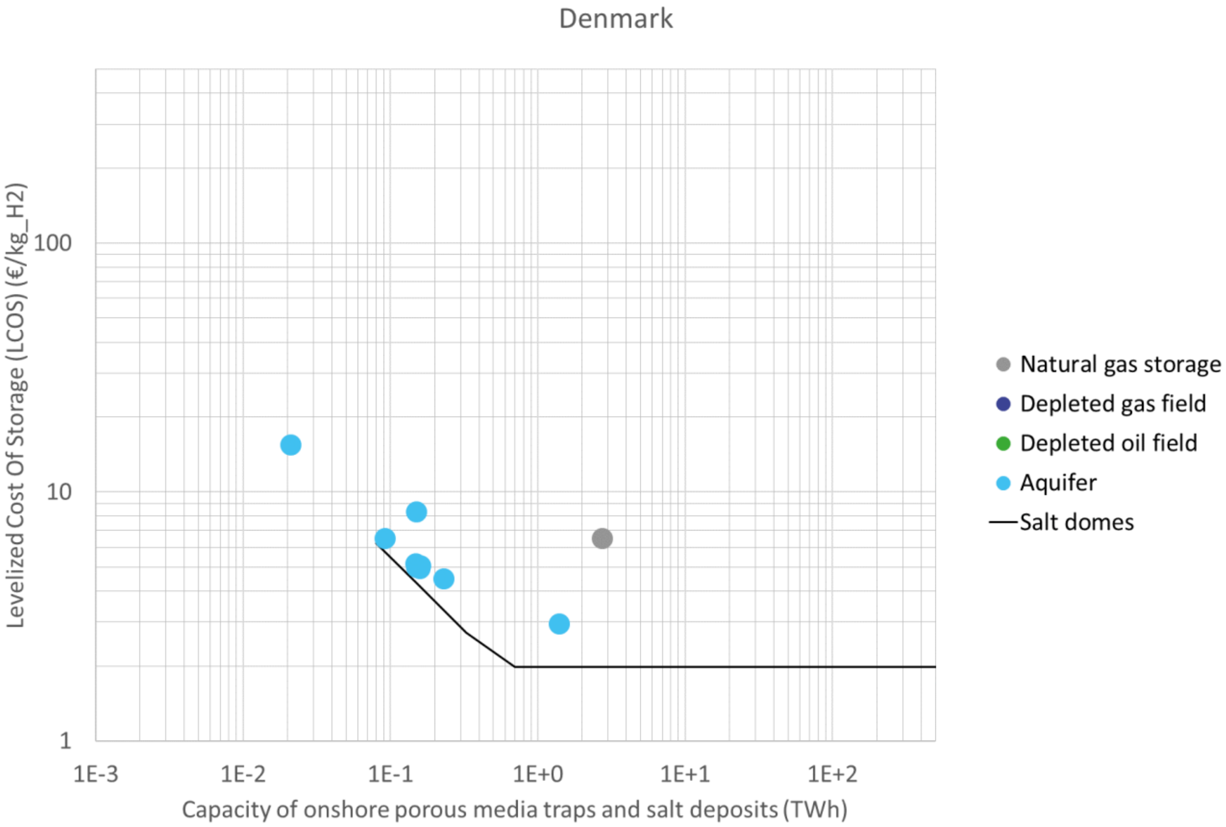


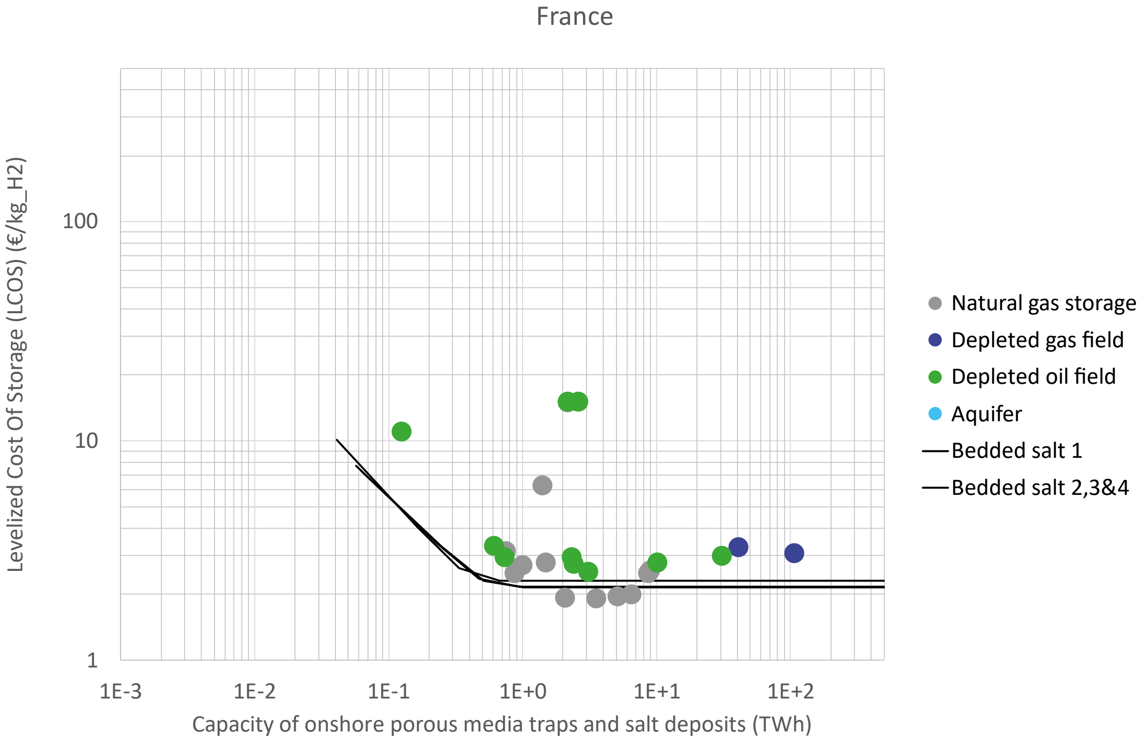



Bulgaria
Levelized Cost Of Storage (LCOS) (€/kg_H2)
100
10
1
1E-3
1E-2
1E-1
1E+0
1E+1
1E+2
Capacity of onshore porous media traps and salt deposits (TWh)
Natural gas storage
Depleted gas field
Depleted oil field
Aquifer
Salt domes

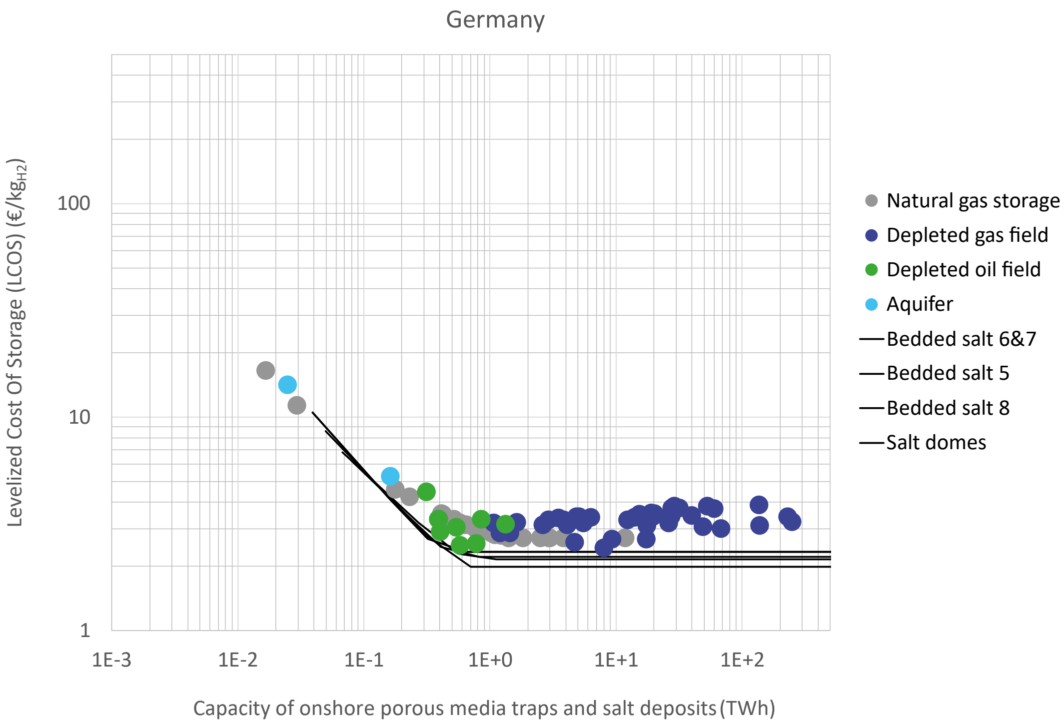

Croatia
Levelized Cost Of Storage (LCOS) (€/kg_H2)
100
10
1
1E-3
1E-2
1E-1
1E+0
1E+1
1E+2
Capacity of onshore porous media traps and salt deposits (TWh)
Natural gas storage
Depleted gas field
Depleted oil field
Aquifer


Czechia
Levelized Cost Of Storage (LCOS) (€/kg_H2)
100
10
1
1E-3
1E-2
1E-1
1E+0
1E+1
1E+2
Capacity of onshore porous media traps and salt deposits (TWh)
Natural gas storage
Depleted gas field
Depleted oil field
Aquifer

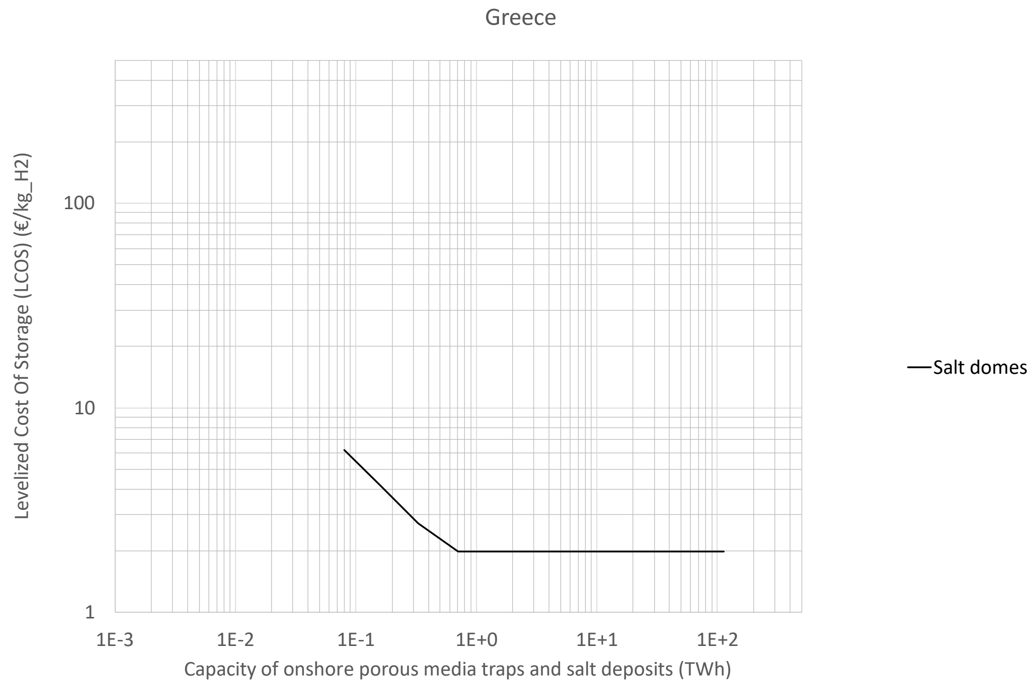

Denmark
Levelized Cost Of Storage (LCOS) (€/kg_H2)
100
10
1
1E-3
1E-2
1E-1
1E+0
1E+1
1E+2
Capacity of onshore porous media traps and salt deposits (TWh)
Natural gas storage
Depleted gas field
Depleted oil field
Aquifer
Salt domes

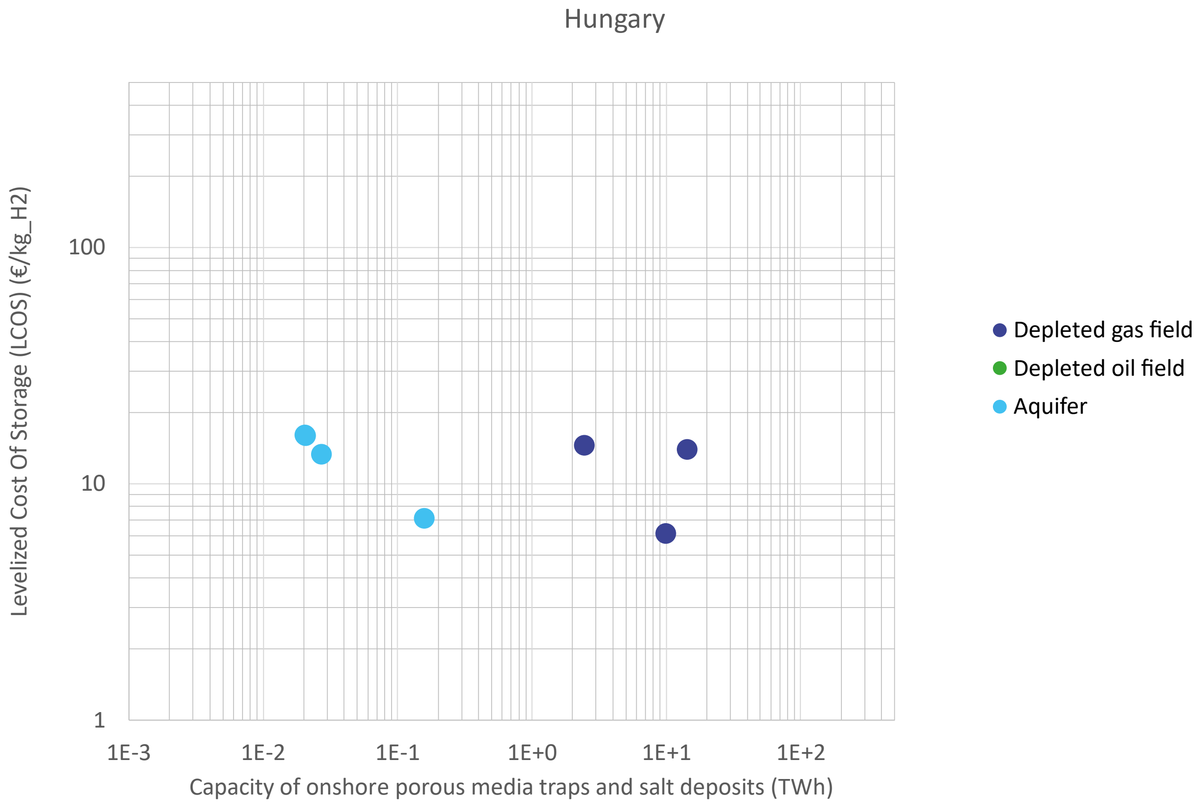


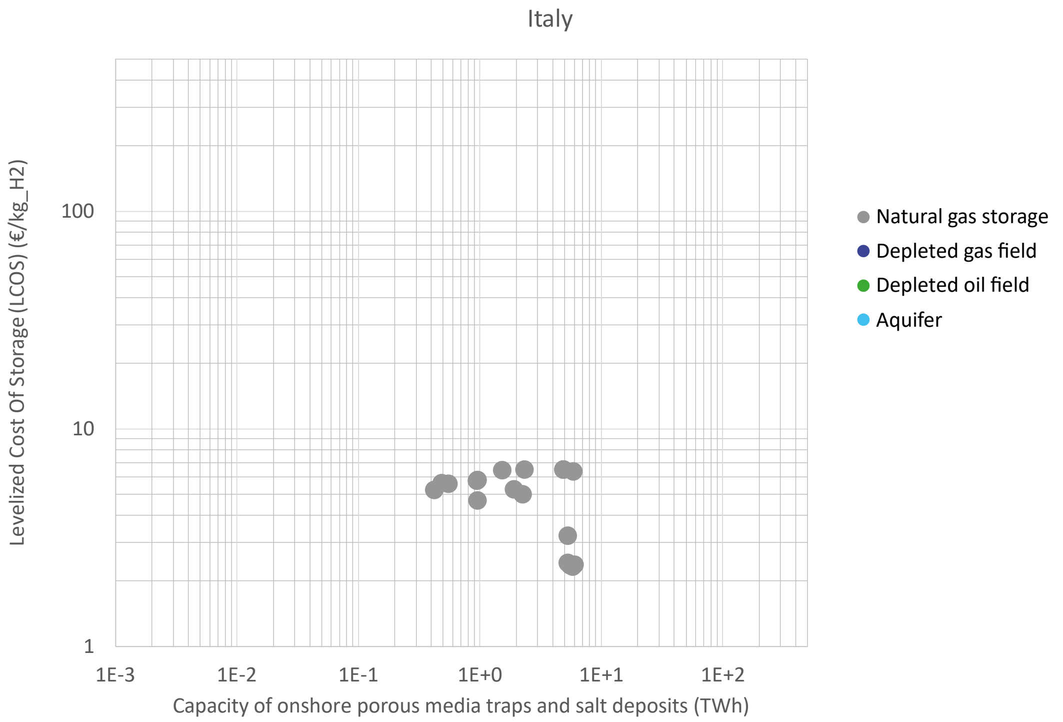
France
Levelized Cost Of Storage (LCOS) (€/kg_H2)
100
10
1
1E-3
1E-2
1E-1
1E+0
1E+1
1E+2
Capacity of onshore porous media traps and salt deposits (TWh)
Natural gas storage
Depleted gas field
Depleted oil field
Aquifer
Bedded salt 1
Bedded salt 2,3&4



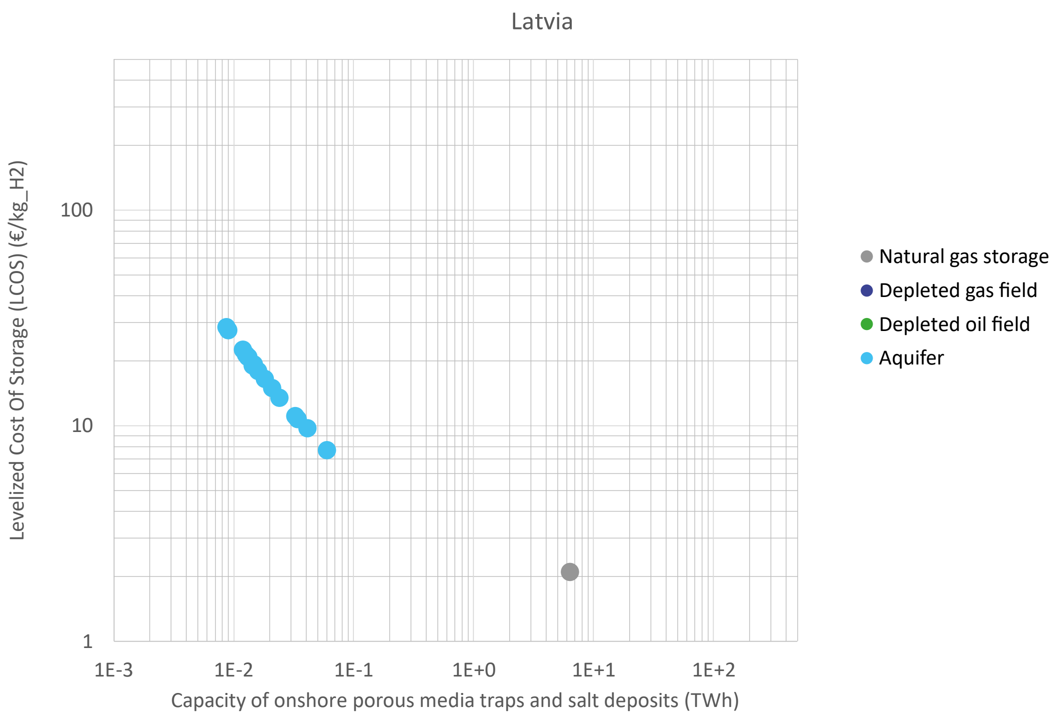
Germany
Levelized Cost Of Storage (LCOS) (€/kgH2)
100
10
1
1E-3
1E-2
1E-1
1E+0
1E+1
1E+2
Capacity of onshore porous media traps and salt deposits (TWh)
Natural gas storage
Depleted gas field
Depleted oil field
Aquifer
Bedded salt 6&7
Bedded salt 5
Bedded salt 8
Salt domes


Greece
Levelized Cost Of Storage (LCOS) (€/kg_H2)
100
10
1
1E-3
1E-2
1E-1
1E+0
1E+1
1E+2
Capacity of onshore porous media traps and salt deposits (TWh)
Salt domes

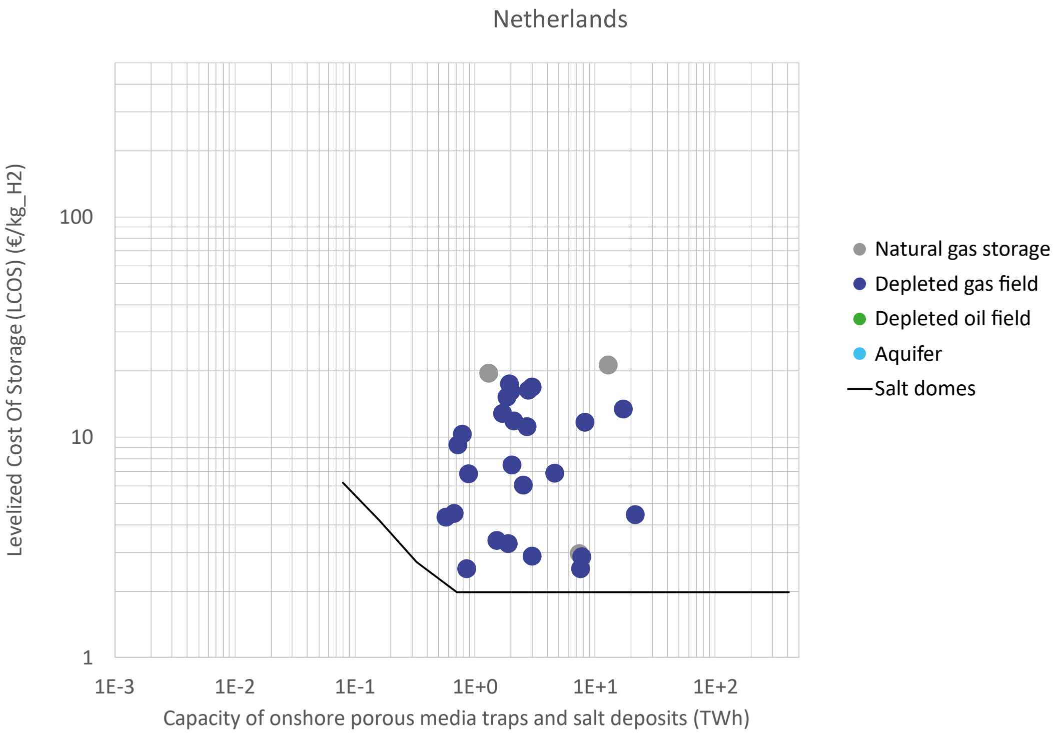

Hungary
Levelized Cost Of Storage (LCOS) (€/kg_H2)
100
10
1
1E-3
1E-2
1E-1
1E+0
1E+1
1E+2
Capacity of onshore porous media traps and salt deposits (TWh)
Depleted gas field
Depleted oil field
Aquifer

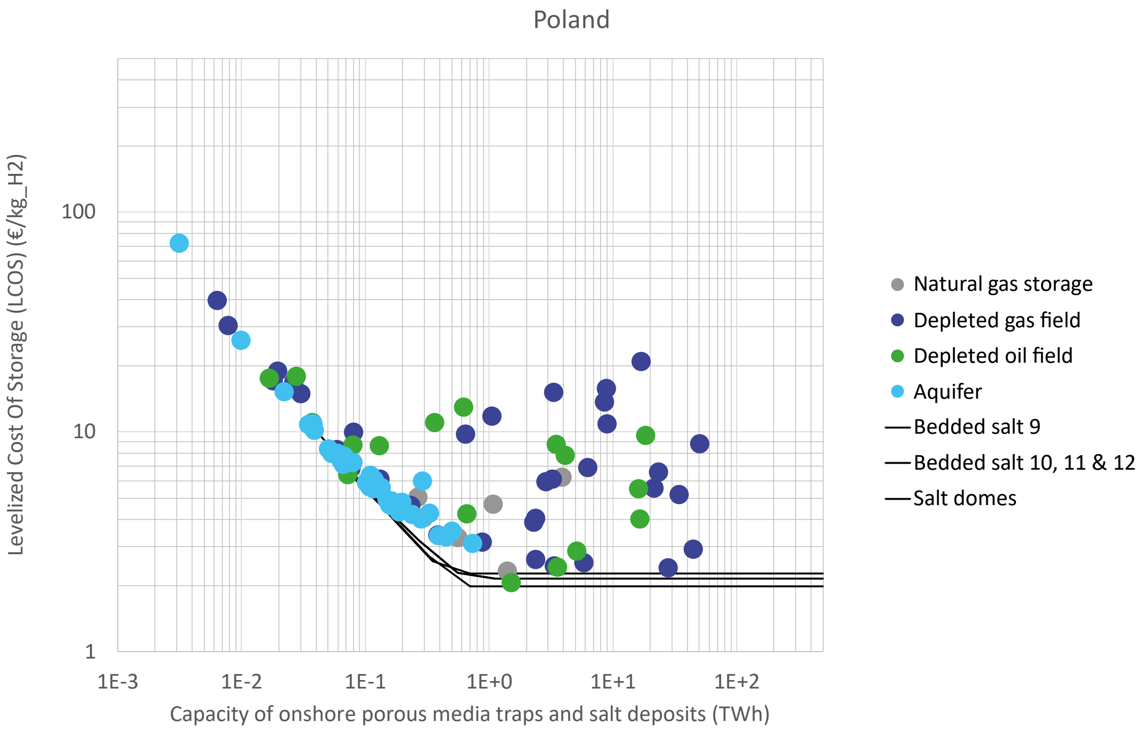


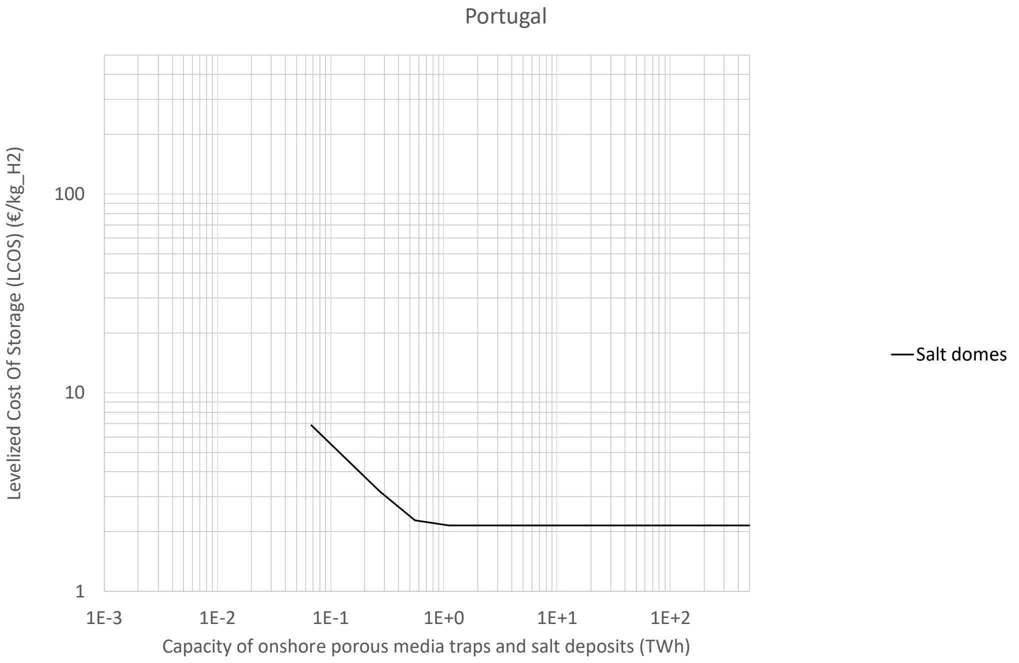
Italy
100
10
1
1E-3
1E-2
1E-1
1E+0
1E+1
1E+2
Levelized Cost Of Storage (LCOS) (€/kg_H2)
Capacity of onshore porous media traps and salt deposits (TWh)
Natural gas storage
Depleted gas field
Depleted oil field
Aquifer



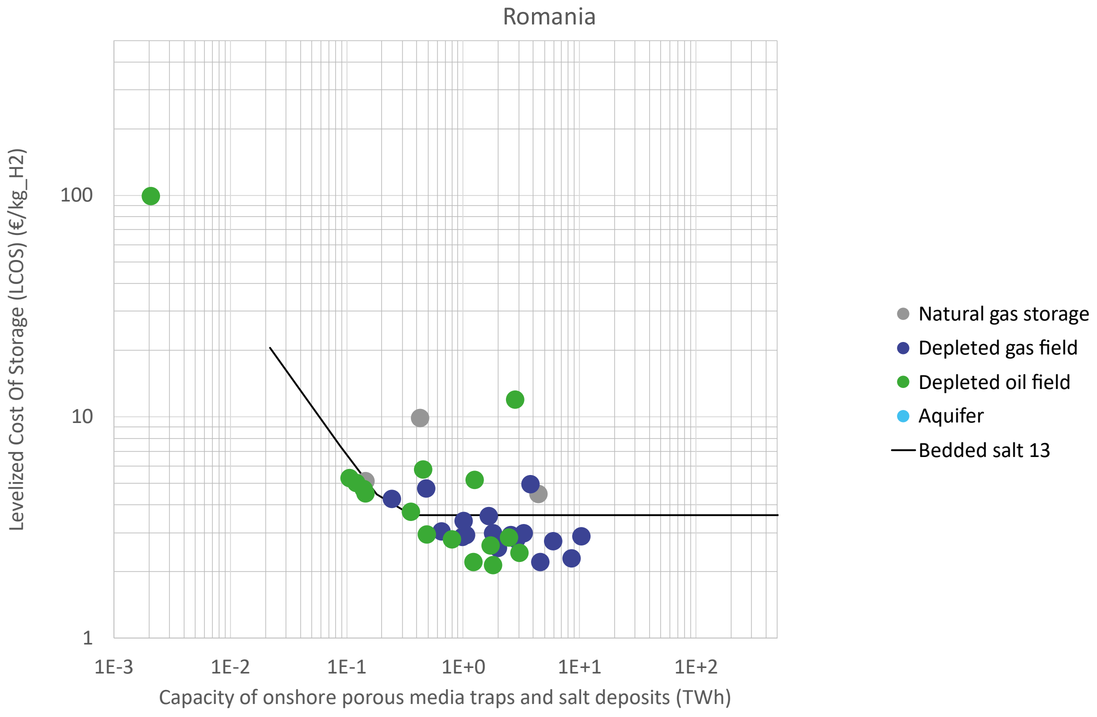
Latvia
100
10
1
1E-3
1E-2
1E-1
1E+0
1E+1
1E+2
Levelized Cost Of Storage (LCOS) (€/kg_H2)
Capacity of onshore porous media traps and salt deposits (TWh)
Natural gas storage
Depleted gas field
Depleted oil field
Aquifer


Netherlands
Levelized Cost Of Storage (LCOS) (€/kg_H2)
100
10
1
1E-3
1E-2
1E-1
1E+0
1E+1
1E+2
Capacity of onshore porous media traps and salt deposits (TWh)
Natural gas storage
Depleted gas field
Depleted oil field
Aquifer
Salt domes

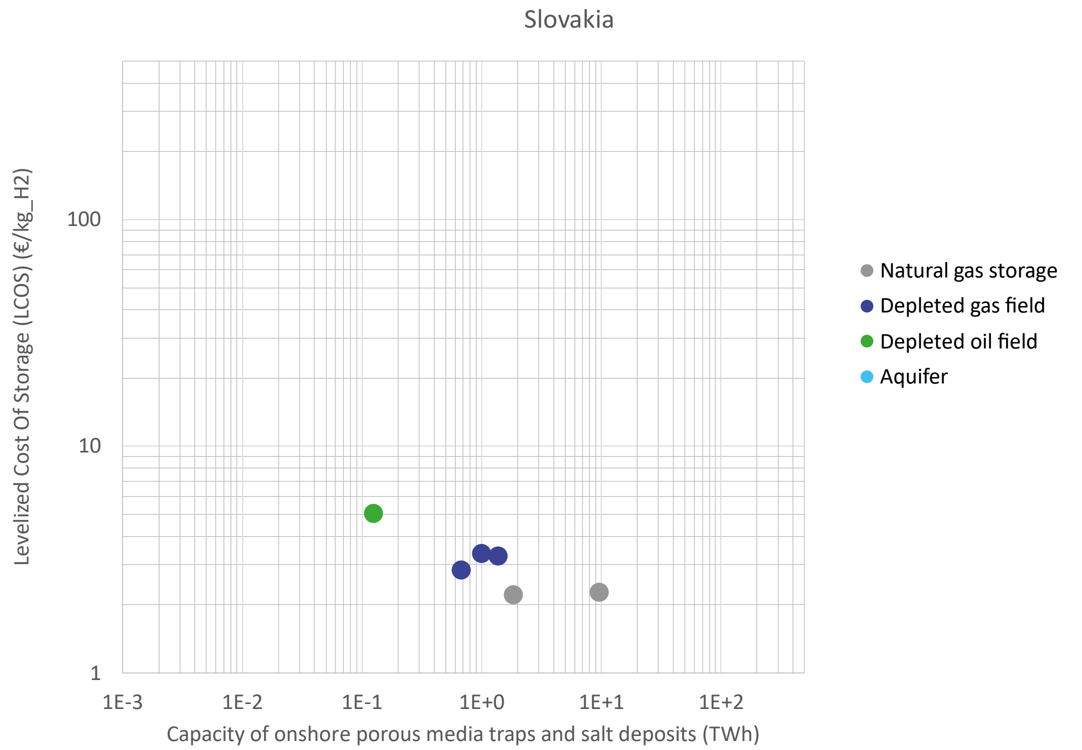

Poland
Levelized Cost Of Storage (LCOS) (€/kg_H2)
100
10
1
1E-3
1E-2
1E-1
1E+0
1E+1
1E+2
Capacity of onshore porous media traps and salt deposits (TWh)
Natural gas storage
Depleted gas field
Depleted oil field
Aquifer
Bedded salt 9
Bedded salt 10, 11 & 12
Salt domes

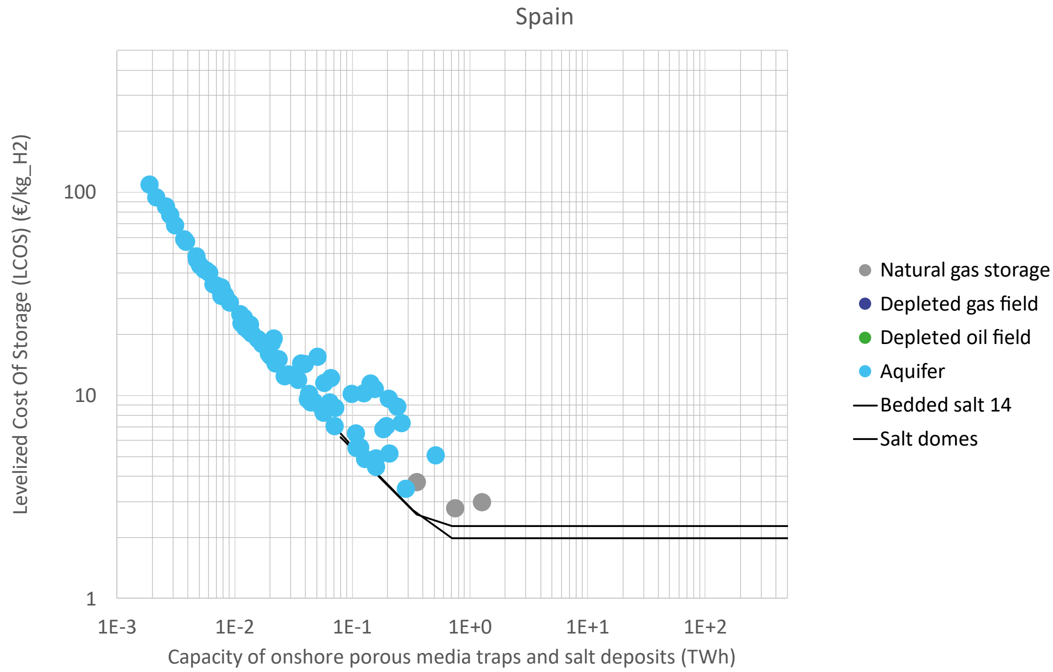


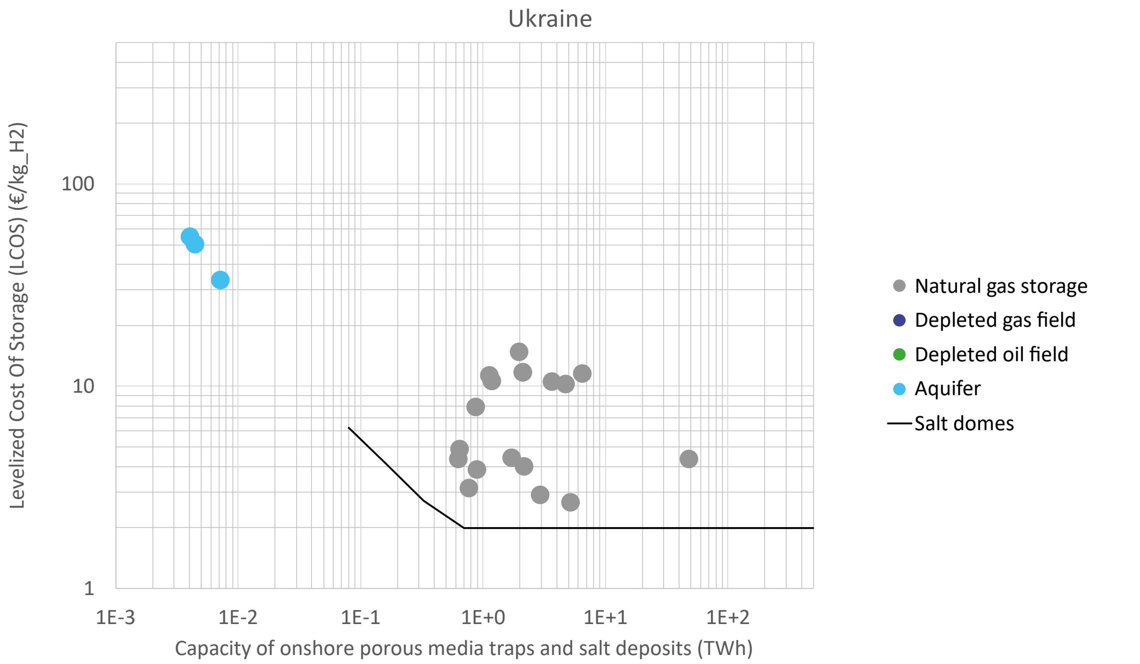
Portugal
Levelized Cost Of Storage (LCOS) (€/kg_H2)
100
10
1
1E-3
1E-2
1E-1
1E+0
1E+1
1E+2
Capacity of onshore porous media traps and salt deposits (TWh)
Salt domes



Romania
Levelized Cost Of Storage (LCOS) (€/kg_H2)
100
10
1
1E-3
1E-2
1E-1
1E+0
1E+1
1E+2
Capacity of onshore porous media traps and salt deposits (TWh)
Natural gas storage
Depleted gas field
Depleted oil field
Aquifer
Bedded salt 13


Slovakia
Levelized Cost Of Storage (LCOS) (€/kg_H2)
100
10
1
1E-3
1E-2
1E-1
1E+0
1E+1
1E+2
Capacity of onshore porous media traps and salt deposits (TWh)
Natural gas storage
Depleted gas field
Depleted oil field
Aquifer


Spain
Levelized Cost Of Storage (LCOS) (€/kg_H2)
100
10
1
1E-3
1E-2
1E-1
1E+0
1E+1
1E+2
Capacity of onshore porous media traps and salt deposits (TWh)
Natural gas storage
Depleted gas field
Depleted oil field
Aquifer
Bedded salt 14
Salt domes



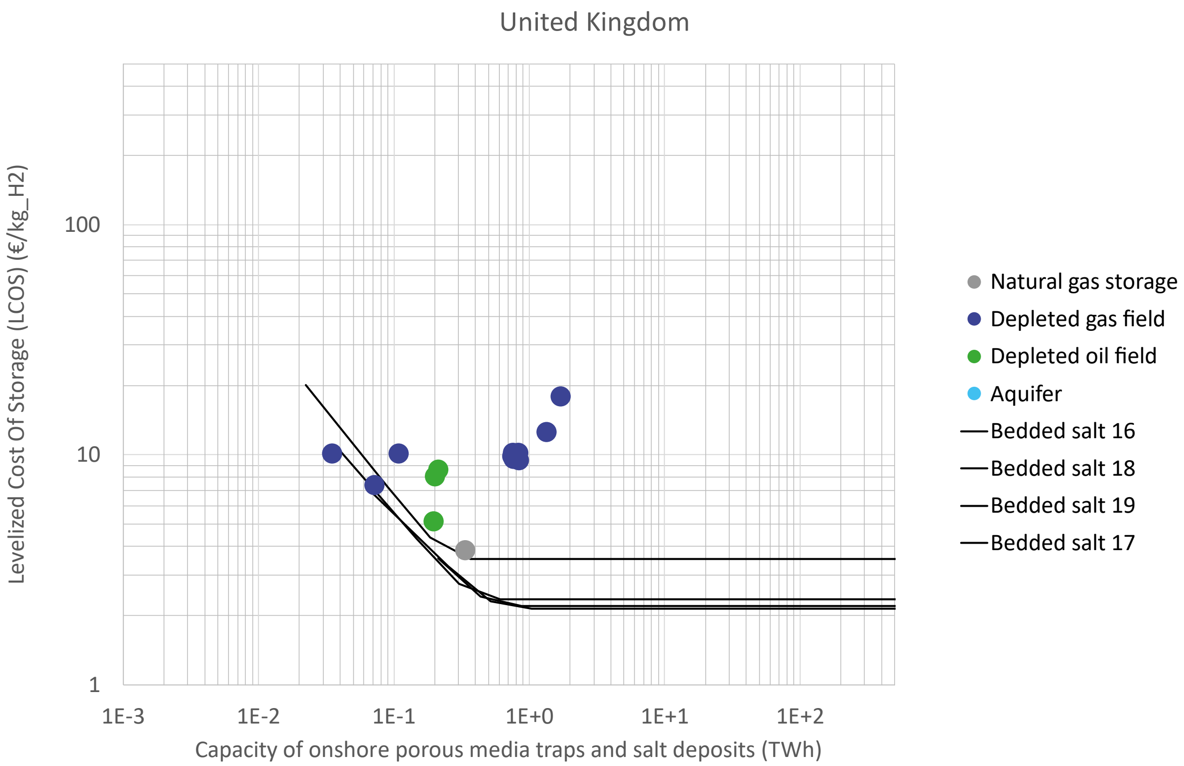


Figure 11: LCOS for onshore porous media and salt caverns per country, Operating Cycle 2 (fast cycle) per capacity, for porous media (for the total capacity of the trap) and for salt caverns (capacity to be chosen by design on the solid line). Bedded salt deposit number refers to the Figure 5.

4. Criteria 2: Suitability Mark

4.1. Methodology

To rank various criteria related to technical issues on porous media traps and salt deposits, the Analytic Hierarchy Process (AHP) method is proposed following the approach proposed by Lewandowska-Śmierzchalska *et al* (2019) to screen and rank for underground hydrogen storage sites in Poland. The main steps for suitability mark assignment are:

- Determining the criteria and assign their score
- Convert the data to score with respect to each criterion
- Determine the weighting factor for the criteria: this is the key step of the AHP methodology
- Get the suitability mark for each site.

4.2. Suitability mark approach

To assess the pros and cons of the different traps identified in WP2 and the salt deposits identified in Europe, qualitative information may be used from WP1 database such as descriptive criteria about the fault, seal, number of plugged and abandoned wells which may relate to the risk level of such a structure. We note that hard geological information is also relevant to assess the suitability criteria, even possibly the most relevant, but it was in many cases already captured by the cost. The **suitability mark is built to be complementary to the cost**. For instance, a depth of 4000 m makes a porous trap or a salt deposit poorly suitable for hydrogen storage, but since this is already captured by the cost, this is not reflected in the suitability mark.

In addition, the type of storage (UGS, DGF, DOF, DSF, Salt Dome and Bedded Salt) may be used to estimate a time to market of such structure as illustrated in D2.2-1 based upon the SPE resource management system as illustrated in Figure 12. Furthermore, as established by WP3, the risk induced by microbiological activity is also included based upon the results from WP3 (Figure 13).

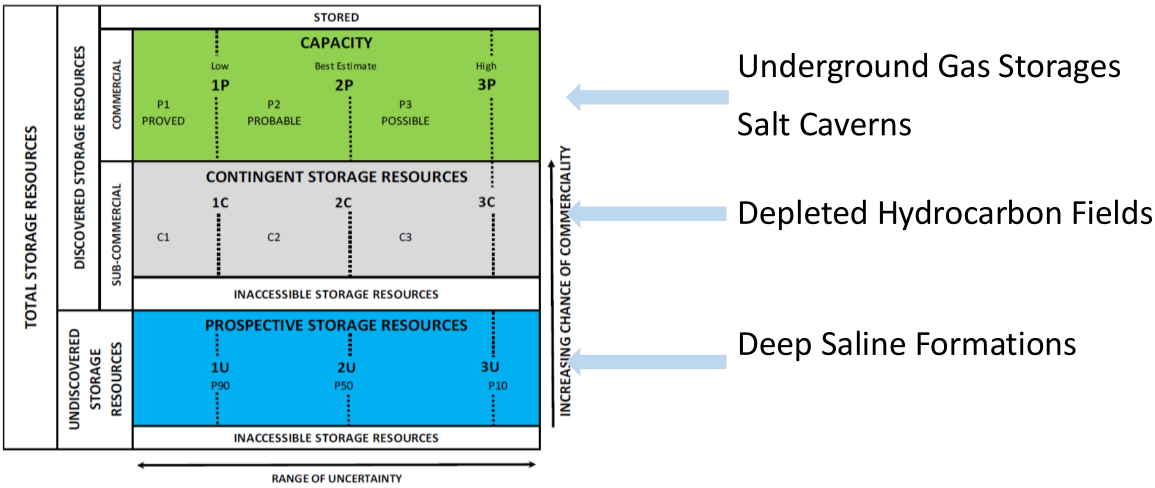


Figure 12: Readiness level of storage types adapted from SPE (2018)

Numerous investigations have shown that geological structures, reservoirs, and storages are populated by a wide variety of highly adaptable anaerobic microorganisms. The degree of colonization depends on chemical and physical factors such as availability of electron donors (such as hydrogen) and acceptors, mineral composition, salinity, depth (temperature), and many others. The three most important metabolic pathways are sulphate reduction, methanogenesis and acetogenesis.

Porous storages and salt caverns differ in terms of microbiological colonization and possible metabolic processes. The cyclic operation regime leads to constant supply of substrates to the microorganisms in particular around the wells-where biofilms formation or chemical precipitation, e.g., FeS, may occur.

Underground storages with temperatures above 90 °C can be considered relatively safe with respect to microbial processes. The salinity of the porous storage formation water or salt cavern sump is the main criterion for microbial growth. Increasing salinity requires specific adaptations of the cells due to the osmotic pressure and limits the possible diversity to halotolerant/halophilic microorganisms for salt caverns. The combined effect of temperature and salinity enhanced their impacts on microbial processes.

The major risk of hydrogen storage is linked to sulphate-reducing microorganisms (H_2S, formation, corrosion, acidification, biofilm formation, precipitation (FeS). Activation of microbial activities by hydrogen may be detrimental since organic substances (biomass) are formed and secondary metabolic pathways (e.g., formation of biopolymers) are enabled. Possible residual hydrocarbons represent an additional source of carbon.

Although a case-by-case assessment of underground storages is necessary, the microbiological risk factors are summarized in Figure 13 for porous media and salt caverns.

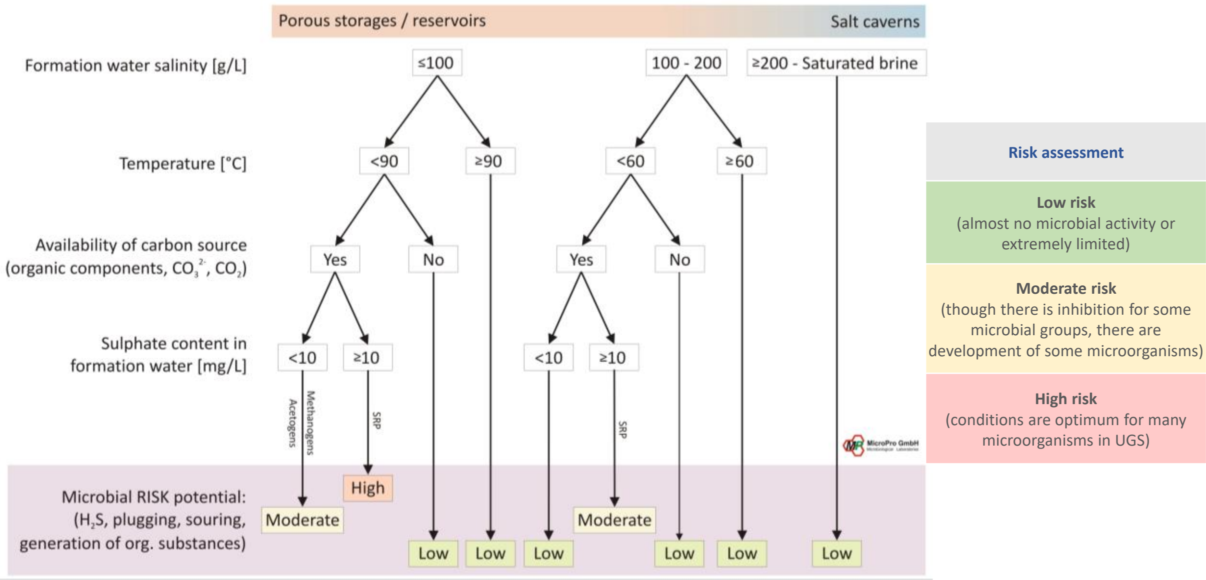


Figure 13: Microbiological risk estimates for underground hydrogen storage in porous media and salt cavern (From D3.4)

The highest suitability mark reflects the best storage conditions based upon the selected set of criteria. The criteria are then evaluated from poor to best conditions in various number of classes on a numerical scale (from 1 to 10 respectively).

4.2.1. Definitions of the criteria

From WP1 database, several parameters were collected which could be used to assess the storage weaknesses and strengths:

- Lithology of the seal (LITHOLOGY_SEAL) which describe the main facies which are identified in the cap rock of the traps: (Sandstone, Carbonate, Limestone, Clay, Shale, Salt…)
- The estimated minimum thickness of the seal (MIN_SEAL_THICK)
- The known fault in the primary caprock above the storage formation (FAULT_THR_OVERBURDEN)
- The number of plugged and abandoned wells which is compared to the total well count penetrating the trap (ABANDON_WELL_RATIO).
- Lithology of the storage (LITHOLOGY_STORAGE) which describe the main facies which are identified in the traps (Sandstone, Carbonate, Limestone, …)

As illustrated in Figure 12, the type of storage would define the time-to-market level of the trap (READINESS). Similarly, the risk of MICROBIOLOGICAL activity is estimated on Figure 13.

4.2.2. Definitions of the score for each criterion

For each criterion, an undefined class is set to handle the lack of information with a minimal score to penalize the trap in the ranking.

For the LITHOLOGY_SEAL, classes range from 0 (unknown) to 10 (very good):

Class	Score
not known	0
Sandstone, Conglomerate	1
Carbonate	1
Limestone	1
Siltstone	3
Clay, Claystone	4
Marl, Clay marl	5
Mudstone	6
Shale	7
Evaporite	8
Anhydrite	8
Salt	10

For the FAULT_THR_OVERBURDEN, classes range from 0 (unknown) to 9 (no fault):

Class	Score
not known	0
Faults present, displacement greater than thickness of the seal	3
Faults present, displacement is less than thickness of the seal	5
No faults cut the primary seal	9

For the MIN_SEAL_THICK parameter, 6 classes are defined based upon the range of thicknesses identified in the WP1 database. Different definition of the classes might be more appropriate to better represent the geological knowledge at the country level. However, to be consistent at the continental level, the classes were defined on the whole range of thicknesses for WP1 database.

Thickness (m)		Score
0	1	0
1	5	1
5	10	3
10	50	5
50	500	7
500		10

For the ABANDON_WELL_RATIO, 4 classes are defined to quantify the risk associated with a large number of abandoned wells which reflect a long development history and might create a risk for the storage development.

Class	Score
not known	1
nb_abandon_wells /nb_wells ≥ 1	3
nb_abandon_wells /nb_wells < 1	7
nb_abandon_wells = 0	9

The READINESS is defined according to the type of traps following Figure 12 but the hydrogen quality and mixing issues are handled through the cost which tends to favour Deep Saline Formations over Depleted Oil Fields:

Class		Score
Porous media	Deep Saline Formations	2
	Depleted Oil Field	3
	Depleted Gas Field	7
	Underground natural Gas Storage	9
Salt caverns	Salt caverns ready for 1st hydrogen fill	9
	Salt caverns requiring heavy field works	6

The MICROBIOLOGICAL risk is defined according to Figure 13 as:

Class	Score
Not enough information (either salinity, temperature, carbon or sulphate source)	1
High risk	3
Moderate risk	5
Low risk	7

For the LITHOLOGY_STORAGE, classes range from 0 (unknown) to 9 (very good):

Class	Score
Not known	0
other	1
Limestone	3
Carbonate	5
Conglomerate, gravel	6
Sandstone	7
Salt cavern	9

4.2.3. Weighting factor for Analytic Hierarchy Process

The score is assigned to each trap and for each criterion and then summed-up for each trap.

The Analytic Hierarchy Process aims at comparing the relative importance of different criteria with respect to each other. The typical scale is defined below:

	Criteria scale
criteria 1 and 2 are equally important	1
1 is slightly more important than 2	3
1 is strongly more important than 2	5
1 is very strongly more important than 2	7
1 is extremely strongly more important than 2	9

Thus, the pair-wise criteria comparison leads to a 7x7 matrix which reflects the expert opinion of the author.

	READINESS	LITHOLOGY_ SEAL	MIN_SEAL_ THICK	FAULT_THR_ OVERBURDEN	ABANDON_ WELL_RATIO	MICROBIOL OGICAL	LITHOLOGY _STORAGE
READINESS	1.00	3.00	3.00	3.00	3.00	1.00	3.00
LITHOLOGY_SEAL	0.33	1.00	3.00	1.00	3.00	3.00	1.00
MIN_SEAL_THICK	0.33	0.33	1.00	1.00	1.00	0.33	1.00
FAULT_THR_OVERBURDEN	0.33	1.00	1.00	1.00	1.00	0.33	1.00
ABANDON_WELL_RATIO	0.33	0.33	1.00	1.00	1.00	0.33	3.00
MICROBIOLOGICAL	1.00	0.33	3.00	3.00	3.00	1.00	3.00
LITHOLOGY_STORAGE	0.33	1.00	1.00	1.00	0.33	0.33	1.00

The influence of the expert opinion was challenged by some of CO2Geonet partners but did not significantly alter this assessment for the traps.

After normalization and data consistency check (see Türk *et al* (2021) and Lewandowska-Śmierzchalska *et al* (2019) for application to different contexts and Munier *et al* (2019) for a mathematical and numerical details on the method), the weighting factor for each criterion is:

	Weights
READINESS	26,2%
LITHOLOGY_SEAL	19,3%
MIN_SEAL_THICK	7,4%
FAULT_THR_OVERBURDEN	8,7%
ABANDON_WELL_RATIO	9,6%
MICROBIOLOGICAL	20,8%
LITHOLOGY_STORAGE	8,0%

These weights aim at normalizing the influence of the different criteria in the mark. The consistency of this analysis resulting from the pair-wise comparison of the different criteria is valid with a consistency ratio as defined by Saaty (2008) at about 9.3%.

4.3. Suitability mark results

The suitability mark reflects the expected quality of the hydrogen storage based upon the selected criteria when considering a conversion to an underground hydrogen storage. The highest the suitability mark, the most appropriate the storage conversion.

As expected, and displayed in Figure 14 for all onshore traps, the underground gas storages and depleted gas fields have higher technical marks than depleted oil fields and deep saline formations. As such they offer the best opportunity for conversion to underground hydrogen storages.

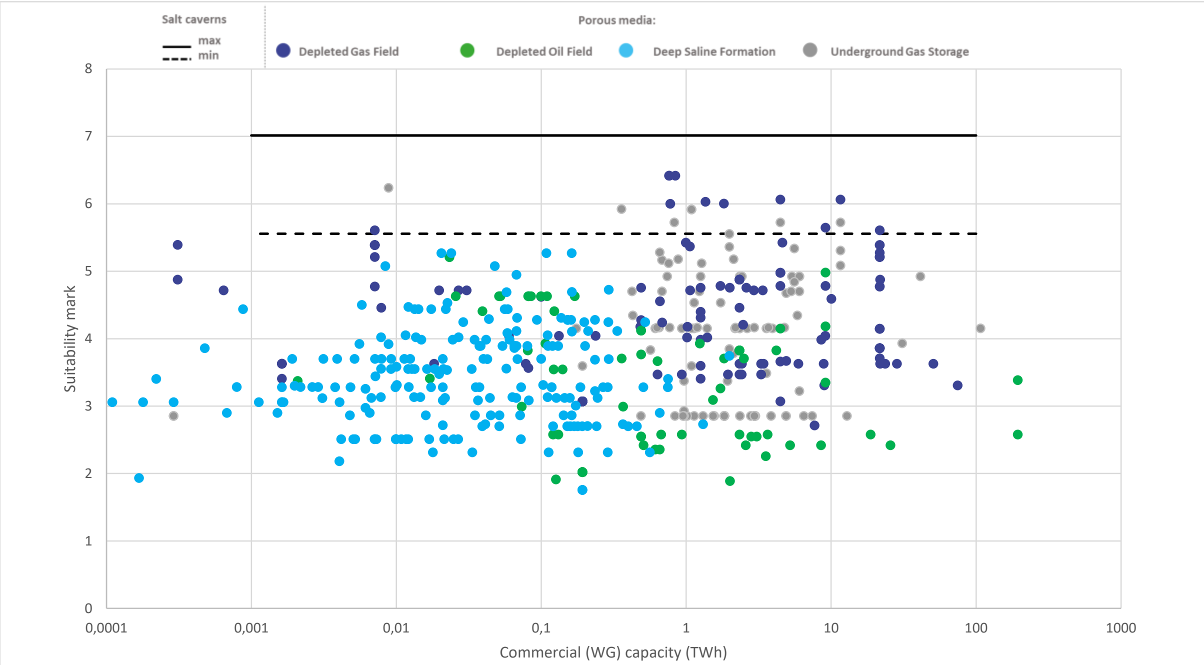


Figure 14: Suitability mark of traps based upon the commercial (Working Gas) capacities

Concerning the salt deposits, either within a salt dome or in bedded salt, since a storage site is largely engineered to the required capacity, the "commercial capacity" is not given by the geology. Salt caverns are therefore represented by two lines corresponding to different quality of the salt. The high suitability score obtained by salt cavern storage is also due to expected low microbiological risk.

Obviously, at the country level, the analysis leads to a preferred option towards the development of onshore underground hydrogen storages in exiting underground gas storages or depleted gas fields as shown in Figure 15. Based upon publicly available information collected within Hystories database, this may be possible in most countries except when then the geology is not suitable or no gas field is reported onshore such as Cyprus, Estonia, Finland, Sweden, Portugal, Malta, Luxembourg, Lithuania and Ireland.

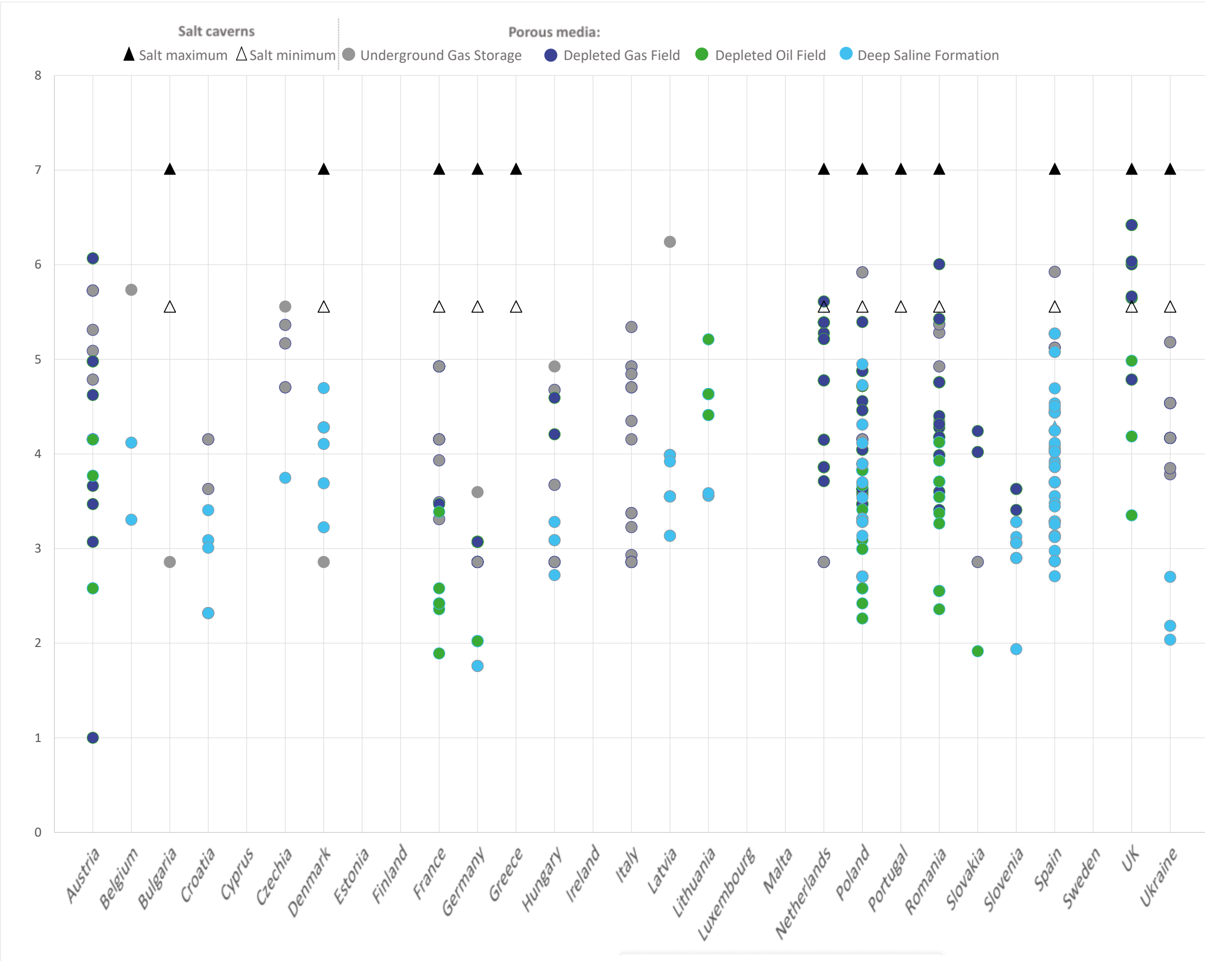


Figure 15: Suitability mark of porous media traps and salt per country

5. Conclusions

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

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

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

These marks have been computed for 805 porous media traps, 18 bedded salt deposits and salt domes found in EU-27+UK+Ukraine:

- The Levelized cost of storage are given for either the seasonal (Figures 6 and 7) and fast cycles (Figures 9 and 10)
- The suitability mark is given in Figure 14.

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

- The Levelized Cost Of Storage (LCOS) Increases significantly when the storage site capacity is smaller than the values considered for the Conceptual design (D7.1-1): 250 MM Sm^3 capacity site for salt caverns (21 000 tons; 0.7 TWh) and a 550 MM Sm^3 capacity for porous media (46 000 tons, 1.5 TWh LHV)
- **For seasonal cycles, the LCOS is 1.1 €/kg (32 €/MWh; 90 k€/MMSm^3) for aquifers and depleted fields; 2.3 €/kg (70 €/MWh; 200 k€/MMSm^3) for salt caverns**[8]. Porous media are found significantly less expensive than salt caverns. This is consistent with the current natural gas storage industry, dominated by seasonal cycles and where most capacity is found in porous storages
- **For fast cycles, the LCOS is 2.6 €/kg (77 €/MWh; 216 k€/MMSm^3) for aquifers and depleted fields; 2.0 €/kg (59 €/MWh; 170 k€/MMSm^3) for salt caverns**[8]. Costs of both technologies are found to be close. Such opportunities of fast cycle storage at relatively low cost in porous media correspond to reservoirs with particularly favourable characteristics
- The suitability marks of salt caverns are found significantly higher than those of porous traps, reflecting the relatively higher maturity and the lower technical risk, notably related to the microbiological activity. **From the suitability mark point of view, the salt caverns, and then the existing natural gas storages and depleted gas fields offer the best opportunity for the creation of underground hydrogen storages.**

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

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

6. Acknowledgment to previous Hystories works and to the Advisory Board support

This ranking work builds upon results obtained in most other Hystories work packages:

- The data collection of the publicly available characteristics of porous media traps at European scale was a major work done in WP1 by all CO2Geonet participating parties. This data was used in WP2 to estimate the storage capacity of each of these 800+ traps through a meticulous work. This capacity estimated in WP2 and several other quantitative parameters from WP1 database are the key inputs to the cost model for porous media.
- Complementary qualitative characteristics from WP1 traps database, such as the presence of faults and abandoned wells, the quality of their cap-rock are also directly used in the Suitability mark.
- The risk assessment scale related to the impact of the microbiological activity in storages, one of the influential part of the suitability mark, was developed in WP3 large scale laboratory test program. It was enabled by the strong support of Hystories Advisory Board members who provided brine samples and the authorization to use it in this public research project.
- The results obtained on a large selection of steel grades (also kindly provided by the Advisory Board) through the laboratory tests in hydrogen conditions in WP4 were influencing in setting the "Material Cost Factor" to 1 in the cost model (which corresponds to using carbon steel, rather than stainless steel).
- The seasonal cycle and the fast cycle are defined from the minimization of the overall cost for the European Energy System in a 2050 horizon, a result of WP5.
- The parametric cost model for the development of a green-field storage site, able to adapt at best to the relevant characteristics of both porous media and salt caverns, was previously built in WP7 for the purpose of this application.

The present report and site ranking is therefore somehow just adding a last piece to many already developed by other participants to the work and could not have been done without it. All the Hystories team (Partners, Third Parties and Advisory Board members) enabled to produce these results: www.hystories.eu/partners-hystories

Last, we sincerely thank Nikolaus Weber for his help in bringing insights on their Caglayan et al. (2020) research work.

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Hystories D5.3 European energy system model description.

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Hystories project consortium

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