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Impact of Infrastructural Constraints on the Potential for Hydrogen Storage in European Countries

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Abstract

In recent years more and more salt cavern projects for hydrogen storage have been launched in European countries, most of them addressing research or demonstration objectives. Nevertheless, with the announced projects the European storage industry is still far from reaching the capacity targets for the next decades that are communicated in government strategies or studies about meeting climate goals. On the other hand, significant geological potential for the development of salt caverns is known in several European countries. For some countries, studies about the theoretical hydrogen storage capacity based on technical limitations exist, but up to now, there is no evaluation of the additional constraints by the need to connect the storage sites with the relevant infrastructure, especially for the stored hydrogen and for the brine produced in the leaching process. The joint project HyPSTER, that targets the demonstration of hydrogen cycling in an existing salt cavern in Étrez, France, as well as the development and validation of cavern modelling tools, also includes the application of these tools for optimizing salt cavern configurations for hydrogen storage in Europe. To support the assessment of potential storage sites and inform investment decisions for the development of further hydrogen storage projects, these modeling tools have been used to re-evaluate realistic hydrogen storage potentials in several European countries considering the impact of infrastructural constraints. At first, a set of cavern configurations representative of existing gas storages in Europe was defined and compared regarding their hydrogen storage performance using a modelling tool mainly regarding cavern thermodynamics, but also including creep closure. In the next step, literature data on the occurrence and properties of salt deposits in Germany, France, Denmark, Netherlands and United Kingdom as major European cavern storage operating countries has been evaluated regarding their potential for the leaching of storage caverns and the resulting hydrogen storage capacities. Finally, the potential sites have been restricted to those within certain corridors along the planned European Hydrogen Backbone representing the hydrogen infrastructure and around certain industrial centers for brine offtake or along the coastline. This work now presents an overview of the impact of the applied constraints on the storage potential. The result is a set of more realistic figures of storage potentials for the evaluated countries than the pure geological potential. These numbers are compared with storage demand forecasts from literature, which shows that even under the applied restrictions there is still sufficient potential to meet the expected demand for the next decades.

Key words: hydrogen storage, salt caverns, geological potential, infrastructure, brine disposal, chemical industry, European hydrogen backbone

1. Introduction

In 2020, the European Commission has adopted its hydrogen strategy [1]. Since then, it has been clear to most energy sector stakeholders that large-scale hydrogen storage will be a key part of the infrastructure to be created. Several initiatives or projects for the development of such hydrogen storage have been started. The first have already reached some of their intermediate targets. One of these is the HyPSTER initiative, which is the first EU-supported project to demonstrate hydrogen storage in salt caverns. The project explores using simulation tools to model and enhance the design and development of hydrogen storage systems in these caverns. These tools can assess the technical and commercial aspects of different plant configurations.
Besides preparing for the demonstration of hydrogen storage in salt caverns at the Étrez site in France, the project aims to enable the replication of this technology across various European locations. Earlier stages involved developing and publishing representative cavern configurations, geological characteristics, and sample operating cycles [2]. Additional efforts included conducting a sensitivity analysis on storage capacity concerning different cavern properties. These findings are detailed in section 4 of the current work. More details about the work carried out within the HyPSTER project can be found here [3,4]
The next step is to examine the availability of suitable salt formations for cavern development to evaluate the feasibility of replicating cavern storage technology. Although several publications discuss the occurrence of salt deposits across Europe, they typically focus on specific regions or sites. The comprehensive collection of global salt data by Horvath et al. [5] will be utilized for the current evaluations. This study will determine what portion of the total salt deposits is suitable for developing hydrogen storage sites, considering factors like infrastructure development (proximity to the hydrogen backbone and brine disposal options) and the properties of the salt formations.
Using assumptions for a standard cavern and the distances between caverns, the potential for hydrogen storage near the European Hydrogen Backbone (EHB) and brine disposal options has been estimated. These values are compared to the anticipated hydrogen storage demand and existing natural gas storage capacities. Additionally, the timeline challenges for developing hydrogen storage are discussed in relation to the historical development of natural gas storage caverns.

2. Expected storage demand in selected European countries

A comprehensive study conducted in 2021 by Guidehouse for Gas Infrastructure Europe (GIE) [6] estimated Europe's hydrogen storage demand to be 72 TWh (2.5 10^8 MMBtu) by 2030 and 466 TWh by 2050. For Germany, the study projected 16 TWh (5.5 10^7 MMBtu) for 2030 and 111 TWh (1.6 10^9 MMBtu) for 2050, which is significantly higher compared to the recent green paper from the German Ministry for Economics and Climate Protection [7] (2 TWh (6.8 10^6 MMBtu) for 2030 and 74 TWh (2.5 10^8 MMBtu) for 2045). Another recent study by Artelys and Frontier Economics for GIE [8] estimated Europe's total hydrogen storage demand at 45 TWh (1.5 10^8 MMBtu) for 2030 and 270 TWh (9.2 10^8 MMBtu) for 2050 (both based on the lower heating value), which is about 40% lower than the earlier Guidehouse study.

Table 1. Overview of hydrogen demand and hydrogen storage demand in selected European countries (reproduced from [6]).

Country	**Hydrogen demand 2030 [TWh] ([10^6 MMBtu])**	**Hydrogen demand 2050 [TWh] ([10^6 MMBtu])**	**Hydrogen storage demand 2030 [TWh] ([10^6 MMBtu])**	**Hydrogen storage demand 2050 [TWh] ([10^6 MMBtu])**
Denmark	3.1 (11)	22.3 (76)	0.7 (2)	5.3 (18)
France	34.7 (118)	182.1 (622)	8.2 (28)	43.1 (147)
Germany	66.9 (228)	470 (1 603)	15.9 (54)	111.4 (380)
Netherlands	26.6 (90)	133.4 (455)	6.3 (21)	31.6 (108)
United Kingdom	29.1 (99)	244.2 (833)	6.9 (24)	57.9 (198)
Europe (others)	144,1 (491)	916,1 (3 127)	36,9 (126)	212,2 (725)
Europe (total)	**304.5 (1 039)**	**1 968.1 (6 715)**	**72.2 (247)**	**466.4 (1 592)**

Given that these figures are based on models and assumptions, they inherently carry high uncertainty. For the current work, the numbers from the Guidehouse study will be used for comparison with the geological potential despite possibly overestimating the actual storage demand. These figures offer the advantage of enabling country-specific comparisons. Table 1 presents an overview of the projected storage demand for Germany, France, Denmark, the United Kingdom, and the Netherlands.

3. Geological situation in selected European countries

The geological potential for hydrogen storage in salt formations is highly promising and could play a vital role in the shift towards sustainable energy. Salt formations, especially those rich in halite, provide optimal conditions for creating underground storage facilities for hydrogen gas.
Salt formations have unique properties that make them ideal for cavern storage. Their extraordinary low permeability ensures minimal leakage, offering a secure containment environment for hydrogen gas, which is known for its low molecular weight and tendency to diffuse. Additionally, the self-healing properties of salt formations enhance the integrity of these storage facilities, reducing the risk of gas migration.

The geological characteristics of salt formations also contribute to their suitability for hydrogen storage. Their plasticity allows for the creation of caverns through solution mining techniques, such as brine extraction followed by gas injection. This flexibility in cavern construction enables the adjustment of storage capacity to meet varying hydrogen demand.
Moreover, salt formations are often found at significant depths below the Earth surface, providing ample space for large-scale storage facilities without using valuable land surface. This depth also offers stable temperature conditions favorable for the safe storage of hydrogen gas.

Horvath et al. [5] provide an extensive compilation of global salt deposits, offering spatially resolved data on salt occurrence. However, this compilation has the drawback of providing only rough information about the depth, thickness, and quality of the salt. In the current work, it is used for a preliminary evaluation of the geological potential in Germany, France, and Denmark. For Germany and France, own data is used, and additional references are evaluated. The suitable salt deposits in Germany are further assessed using geological data from the Federal Institute for Geosciences and Natural Resources [9] and the results of the InSpEE and InSpEE-DS research projects [10,11]. These references assume that caverns can always be positioned in a dense hexagonal packing, resulting in at least 11 caverns per 1 km², which is a more optimistic approach than chosen in this work (see section 5).

Information on salt deposits in the Benelux countries has been reviewed, with relevant deposits found only in the Netherlands [12-14]. Geological data for the UK was primarily sourced from Horvath et al. [5] and other references [12].

4. Definition of standard caverns and operating cycle

In an earlier phase of the HyPSTER project, the relevant cavern configurations for hydrogen storage in Europe were identified, and a basic description of pertinent salt properties was provided [2]. The effects on long-term storage performance were also examined. Below is a summary of these findings. Table 2 lists the main parameters of typical industrial-scale caverns and examples of where similar caverns can be found. Additional properties investigated include salt creep rates (cases 8-10), injection temperature (case 11), the diameter of the tubing in the access well (case 12), the heat transfer coefficient between the cavern inventory and the surrounding salt rock (case 13), maximum withdrawal rate (cases 14 and 15), and the type of inventory (hydrogen vs. natural gas, case 16).

To study the long-term behavior of the caverns, a simple operating schedule is applied based on an average load cycle for each common year, scaled to nearly the full operating pressure range for each leap year. Figure 1 illustrates this operating schedule as the relative wellhead pressure over time. This relative wellhead pressure represents the pressure variation of each cavern between its individual maximum and minimum operating pressure, which mainly depends on the casing shoe depth and must be assessed specifically for any real cavern in a geomechanical study.

Table 2. Set of industrial-scale cavern configurations.

Parameter	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**	**Case 7**
Depth of last cemented casing shoe [m] ([ft])	600 (1 969)	900 (2 953)	900 (2 953)	900 (2 953)	1 400 (4 593)	1 400 (4 593)	1 400 (4 593)
Geometrical cavern volume [m^3] ([MMcft])	350 000 (12.4)	200 000 (7.1)	500 000 (17.7)	800 000 (28.3)	200 000 (7.1)	500 000 (17.7)	800 000 (28.3)
Cavern height (roof to sump) [m] ([ft])	70 (230)	70 (230)	140 (459)	300 (984)	70 (230)	140 (459)	300 (984)
Exemplary representations	Western UK	Eastern Germany, Western Germany	Denmark, Central France, Eastern Germany, Netherlands, Portugal	Northern Germany, Netherlands	Western Germany	Denmark, Central France, Western Germany	Northern Germany

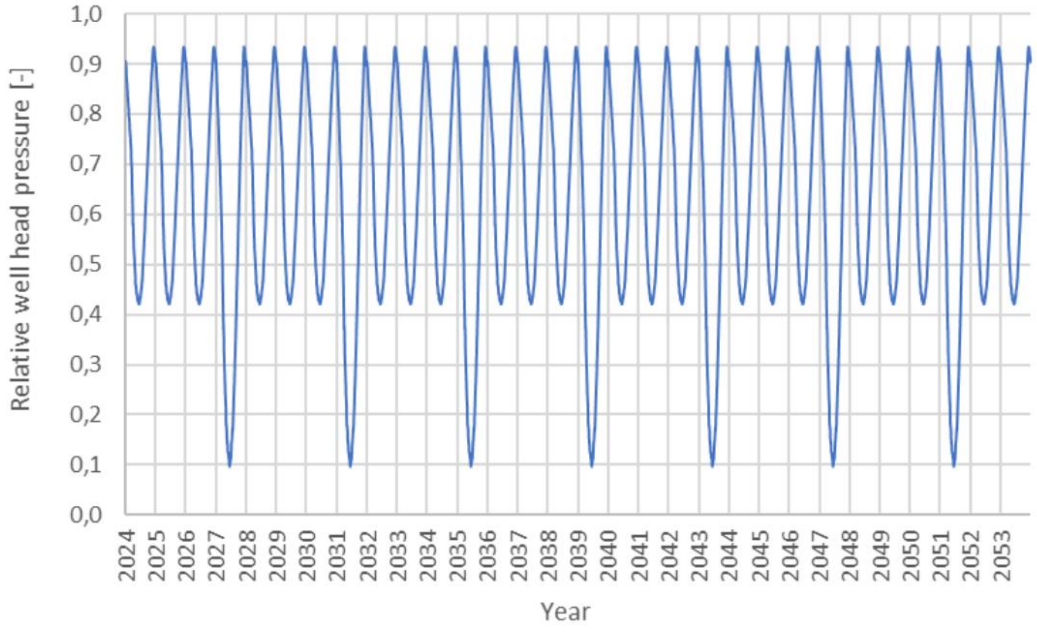

Figure 1. Standard operating cycle for long-term cavern modeling.

Some additional cases have been modeled covering an alternative set of creep parameters (case 08, 12 and 13), variation of the rock temperature (case 09), tubing diameter (case 10), heat transfer coefficient (case 11) and a natural gas storage inventory for reference (case 16). Furthermore, two scenarios are examined, describing the withdrawal and injection of hydrogen at the maximum possible rate, subject to typical limitations of the rate of pressure change in the cavern and the flow velocity in the tubing (+/- 10 bar/day (145 psi/day) and < 20 m/s (66 ft/s), case 14, or +/- 20 bar/day (290 psi/day) and no velocity restriction, case 15).

Regardless of the type of storage inventory, salt caverns converge over time due to salt creep, resulting in a decrease in cavern volume. Typical creep closure rates (volume loss rates) can range from 0.05% per year (shallow caverns) to 1% per year (deeper caverns). These rates depend heavily on rock parameters and operational cycles, and values outside this range have been observed in some cases.

Additionally, creep closure is generally higher in the initial years of operation due to the stronger influence of transient creep. It should be mentioned that the implemented mechanism for creep closure is very simple (see [2]) to allow application for multiple locations without in-depth knowledge of the local salt properties because it is mainly required to assess the cavern volume reduction due to creep closure.

The effects mentioned have been replicated in the modeling of cavern cases over a 30-year operational period. For most cases, the annual cavern volume loss remained below 1% per year, as relative wellhead pressures below 0.4 were only reached every fourth year. However, for a deep cavern (casing shoe at 1 400 m (4 593 ft)) in highly creep-prone salt, an annual volume loss of 2.5% was observed. The modeling confirmed that the long-term development of cavern volume is primarily influenced by static creep behavior. This simplifies the selection of the creep model and software for predictive modeling of storage capacities and performance (see [2] for more details on geomechanical modeling).

The analysis of the modeled cases showed that hydrogen storage capacity is roughly proportional to cavern volume and the depth of the last cemented casing shoe. This relationship can be simplified with acceptable accuracy using an average specific energy storage capacity of 0.27 kWh/m³/m (8 BTU/cft/ft) (lower heating value, see Figure 2). The actual capacity of the modeled cavern can then be calculated by multiplying this specific value by the spatial cavern volume and the depth of its last cemented casing shoe. Deviations from this average value are due to thermal effects and the real gas behavior of hydrogen. It is also important to note that the operating pressure range of the cavern was significantly simplified in the analysis and can have a substantial impact on a real cavern depending on local geology.

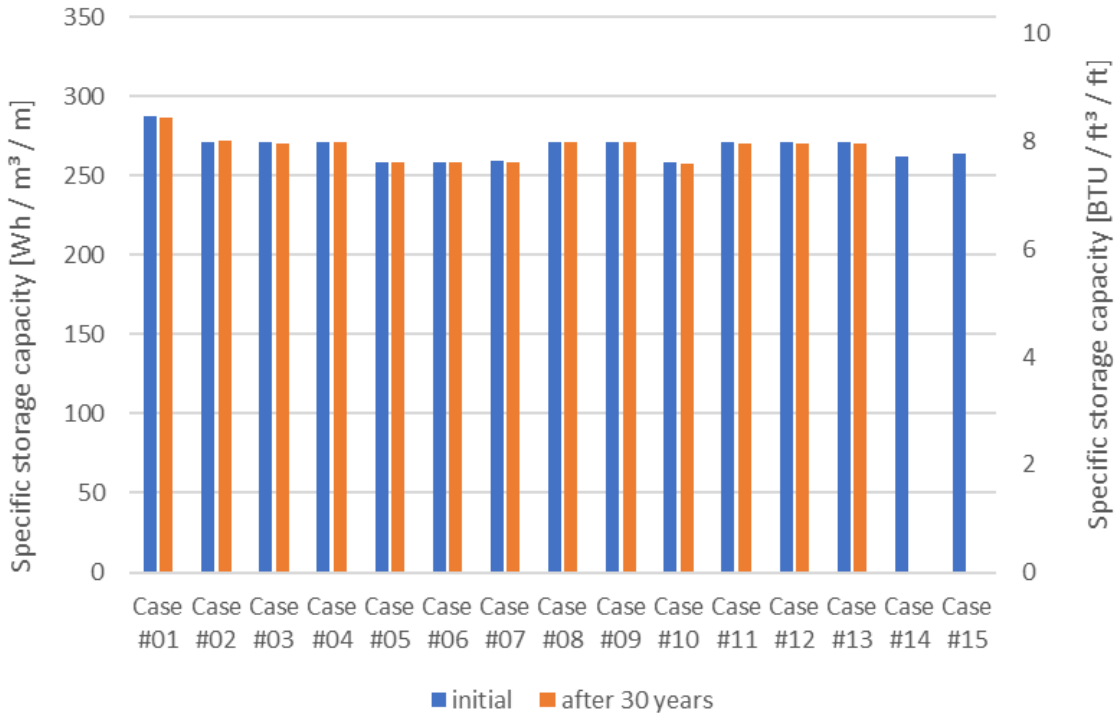

Figure 2. Specific energy storage capacity (lower heating value) of the modeled cavern configurations at beginning and end of the 30 years modeling period. Please note that case 16 (reference case with natural gas inventory) is not shown here due to its different compressibility and heating value.

These findings suggest that optimizing the storage capacity of a salt cavern primarily involves selecting the optimal cavern volume and depth. Both factors are strongly constrained by the local properties of the salt formation and must be addressed individually for each location. Other critical aspects include the costs associated with the chosen configuration. Typically, there are fixed costs for site development and well drilling, along with additional cost components that are more or less proportional to cavern volume and casing shoe depth. To minimize the impact of fixed costs, volume and depth should be chosen as large or deep as possible within geological limitations. However, for casing shoe depths

significantly below 1,500 m (4 921 ft), well costs start to increase disproportionately due to technical challenges with higher pressure ratings, which must be assessed individually for each well. Generally, these considerations are similar to the development of natural gas storage sites. In this work, no significant differences were identified between the dimensioning of storage caverns or sites for natural gas or hydrogen.

The cavern performance modeling indicated that with the given configuration (corresponding to case 03, maximum pressure of 165 bar (2 393 psi), minimum pressure of 60 bar (870 psi), and 7" tubing), the flow velocities in the tubing during withdrawal at 20 bar/day (290 psi/day) would nearly reach a maximum of 200 m/s (660 ft/s), which is not considered realistic. Injection in this case would reach a maximum of 70 m/s (230 ft/s), which is still very high. If flow velocities are capped at 20 m/s (66 ft/s), this cavern can be emptied and filled (i.e., ramping down and up between maximum and minimum pressure) within approximately 14 days each.

The comparison with natural gas (case 16) highlights the significant difference in the energy content that can be stored in a salt cavern using both types of fuel. On a molecular basis, approximately 55 % more natural gas can be stored and withdrawn from the investigated cavern than hydrogen, primarily due to the different compressibility of the gases. In terms of energy content, a cavern filled with natural gas can store and release roughly five times more energy than a cavern filled with hydrogen, owing to the additional difference in heating values. It is important to note that this factor depends on the applied boundary conditions (e.g., operating pressure range); other thermodynamic studies estimate it to be between 4 and 4.5 [15].
According to the study [6], the demand for hydrogen storage in Europe (including the UK) will be 72 TWh (2.5 10^8 MMBtu) in 2030 and 466 TWh (1.6 10^9 MMBtu) in 2050, while the current storage capacity for natural gas in salt caverns is 244 TWh (8.3 10^8 MMBtu). If the scaling factor derived here for case 16 is applied to all these caverns (assuming they can be repurposed for hydrogen storage), they would account for approximately 41 TWh (1.4 10^8 MMBtu) of hydrogen storage capacity. Therefore, even under the highly optimistic assumption that all natural gas storages could be converted to hydrogen by 2030, this would still be insufficient to meet the projected demand. Realistically, a significant portion of the existing natural gas storages will still be needed in 2030 and will not be available for conversion to hydrogen. Consequently, constructing new storage facilities is the only viable way to meet any projected hydrogen storage demand figures [6-8].

5. Conditions for storage development

Although Europe has abundant geological potential for creating salt caverns for hydrogen storage, not all of this potential can be easily realized from a technical and economic standpoint. In addition to the obvious geological factors (like salt depth, thickness or quality), two critical factors limiting the overall feasibility of constructing storage caverns are the distance between the storage site and the locations of hydrogen production, hydrogen consumption, and the distance between the storage site and a suitable site for brine discharge. To assess both aspects generally, some simplifications were necessary. The distance to hydrogen production and consumption is represented by the distance to the nearest section of the planned European Hydrogen Backbone (EHB) [16], which aims to connect the main centers for hydrogen production and consumption in Europe by 2040 or earlier. A maximum distance of 20 km (12 mi) between a salt formation and the EHB is used as a cut-off criterion for the length of the required high-pressure hydrogen access pipeline. Of course, this general approach is a strong simplification, but it allows for demonstrating the effect of this kind of restriction.
Evaluating the feasibility of brine discharge options for specific sites is complex and highly dependent on national legislation. For Germany and France, several cases of brine discharge to the chemical industry or the open sea are known and used as a reference for further evaluation. As a general rule, a maximum distance of 50 km (31 mi) between the storage site and the site of known brine processing plants or the coastline was allowed. This approach is also strongly simplifying the actual options for brine disposal or usage, but it reflects the expectation that brine pipelines incur lower costs and less constraints than high-pressure hydrogen pipelines, and it can be directly applied to the available location data. Furthermore, the results obtained do not imply that locations outside the identified areas cannot be developed commercially. It mainly reflects the tendency that larger distances to the hydrogen grid and brine disposal sites impose a burden on the profitability of storage development, making its commercial feasibility less likely.

As described in section 3, the work of Horvath et al. [5] provides the best overview of the general abundance of rock salt. For the assessment of the technical feasibility to create certain numbers of hydrogen storage caverns, usually, at least the information about the lateral extension of depth, thickness and quality of the rock salt is required, which is just coarsely specified in [5]. However, for Germany and France the authors have access to more detailed data, which is used to derive reduction factors describing the technically usable fraction of the total area of the salt formations from [5]. This scaling approach can then be applied to other countries with less data available. Detailed data was also available for the Netherlands and UK, but with a lower confidence level. Thus, the potential is derived from the available data for these countries, but the results are not used for extrapolation to other countries.

To further illustrate the energy storage capacity of the resulting salt structures it was assumed that seven standard caverns (case 3, see section 4) can be placed per 1 km² (0.39 mi²), corresponding to a hexagonal packing with a distance of 400 m (1312 ft) between the cavern axes. To account for additional safety distances to the outer boundary and potential irregularities in the practical realization of the hexagonal packing a further reduction factor of 0.8 was applied. This results in an average specific storage capacity of 0.7 TWh/km² (6 187 Btu/mi²) (lower heating value of hydrogen).

6. Country-specific evaluation of storage potential

The evaluation of realistic storage potentials was started with Germany and France. In those countries, the project partners possess detailed data about the relevant properties (mainly depth, thickness, lateral extension and quality) of many salt deposits. From the total abundance of rock salt (see section 3), the realistic potential for storage development has been obtained by three reduction steps as specified in section 5. Figure 3 illustrates the results obtained by this process for Germany.

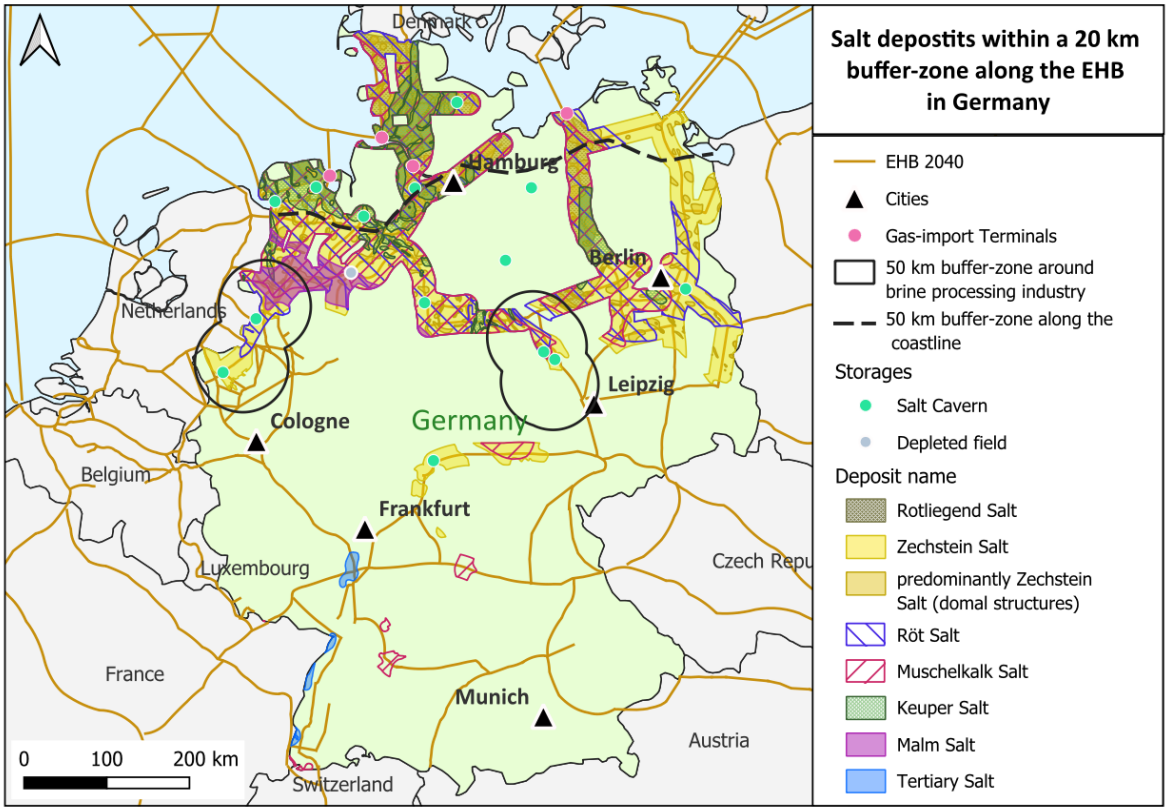

Figure 3. Salt structures in Germany suited for the development of hydrogen storage caverns along the EHB corridor (20 km or 12 mi to each side). This map was created based on data from [5,16]. Additionally, the zones for brine disposal to the open sea or transfer to the chemical industry (50 km or 31 mi distance) are indicated.

When evaluating the overlap of the total salt area in Germany and the corridors along the hydrogen backbone, the results exceed 60 000 km² (23 000 mi²), which is not realistic and impractical due to various technical constraints such as the thickness and depth of the salt formations, and existing surface infrastructure and buildings. A further evaluation of the resulting salt structures based on own geological data applying a minimum salt thickness of 300 m (984 ft), a depth range of 400 m (1312 ft) to 2 000 m (6562 ft) below ground level, sufficient salt quality and availability of ground at the surface leads to a reduced area of 1 598 km² (617 mi²).

The evaluations do not yet account for potential limitations related to the disposal of brine produced during cavern leaching. This aspect can be particularly challenging for site development and may incur prohibitively high costs if no brine discharge options are available near the planned storage site. The chemical industry uptake of brine is considered the most viable option for salt cavern leaching, and historically, brine processing industries have developed around sites with salt production and leaching activities. For the present evaluation, the brine processing centers in western and central-eastern Germany are considered (Figure 3).

Another alternative for brine disposal involves releasing it into the open sea, a practice currently utilized at several sites along the German North Sea coast. This study assumes that this method could be extended to new hydrogen storage facilities along the entire German coastline (Figure 3), although actual implementation would require approval from relevant authorities.

Considering the options for brine disposal significantly narrows down the feasible salt structures for developing new cavern storages (Table 3). A total area of 716 km² (276 mi²) was identified, with the majority being Zechstein salt (mainly diapirs) along the coast, accounting for 571 km² (220 mi²). This represents roughly half of the suitable area identified along the EHB. A smaller portion, 145 km² (56 mi²), comprises inland Zechstein diapirs near brine processing industries.

Scaling factors were derived to compare these figures with those of other countries. The area of salt structures effectively used for cavern construction after considering technical limitations and brine usage or disposal corresponds to approximately 1% of the total area of salt structures along the EHB.
Additionally, there is a potential of 1 036 km² (400 mi²) of bedded salt near brine processing industries. However, the geological data for these locations is limited, leading to significant uncertainty regarding the geological, technical and economic feasibility of cavern construction in these areas.

Other salt deposits, such as those from the Triassic/Jurassic periods, may exist in several areas but are excluded from this evaluation because they are situated directly above the Zechstein salt, and constructing multiple caverns on top of each other is not a common practice in the cavern industry. Tertiary deposits in the Upper Rhine Region are also neglected in this evaluation due to their distance from identified brine disposal options; they could only be considered if alternative brine disposal methods are found.

Considering the distances to the EHB and brine disposal or usage options, Germany's realistic hydrogen storage potential in salt caverns is 501 TWh ($1.7\ 10^9$ MMBtu), considering the standard cavern described in section 5. Another detailed evaluation of geological and technical aspects of the storage potential in Germany was conducted in the projects InSpEE and InSpEE-DS [13,14]. In these works, a total potential of 1,614 TWh ($5.5\ 10^9$ MMBtu) for hydrogen storage caverns in Zechstein salt domes and 1,712 TWh ($5.8\ 10^9$ MMBtu) in other salinars and bedded salt was derived from available literature based on similar technical conditions as applied in the present work, but without considering hydrogen or brine infrastructure connections. The application of the same constraints as in the present work would also lead to a significant reduction of the potential from [13,14].

Examining the existing cavern storage options in Germany reveals a natural gas storage capacity of 165 TWh (5.6 108 MMBtu), stored in approximately 250 caverns [17]. If all natural gas caverns were theoretically converted to hydrogen, 39.6 TWh ($1.4\ 10^8$ MMBtu) of energy could be stored in these existing caverns, assuming no technical limitations for cavern conversion [6]. Additionally, the potential for hydrogen storage in further developed brownfields is about 160 TWh ($5.5\ 10^8$ MMBtu), based on the geology of the salt structures at the storage sites and using the same calculation process.

For France, the evaluation began with the compilation of global salt deposits from [5]. Similar to the initial assessment for Germany, only salt structures within a maximum distance of 20 km (12 mi) from the EHB were selected. The resulting structures are shown in Figure 4, and the total salt area is provided in Table 3.

The largest areas with salt structures near the planned pipelines are found in three regions:

- Aquitaine Basin (Bordeaux),
- East of Paris Basin (Keuper and Muschelkalk salt) and Alsace-Jura Basin (Tertiary salt),
- Bresse Basin and Rhone Valley (Lyon - Marseille).

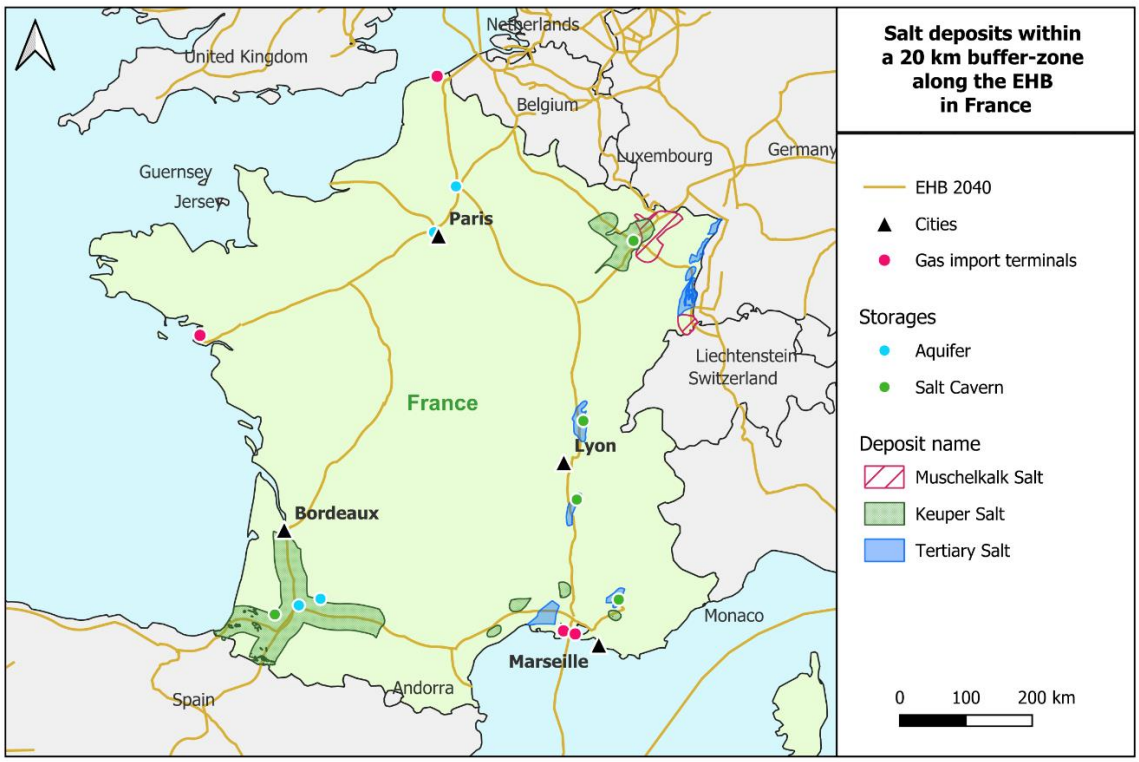

Figure 4. Salt structures in France suited for the development of hydrogen storage caverns along the EHB corridor. This map was created based on data from [5,16].

These identified structures are well-separated, with minimal overlap (except for some overlap of Muschelkalk/Keuper in Eastern France).

As for Germany, the evaluation of the technical feasibility of storage caverns had to rely on additional internal data from the authors (Table 3). This analysis does not include new salt caverns in Southwest France due to insufficient brine disposal options (low acceptability for brine discharge into the open sea) and the limited capacity of the brine processing industry. Additionally, the development of the EHB is considered to be of lower priority in this region than in Eastern France.
Comparing the resulting area for cavern development to the total salt area of the corresponding structures near the EHB yields a fraction of 0.4% that could realistically be used for cavern construction.

According to this evaluation, considering brine discharge options, the total hydrogen storage potential near the EHB in France is approximately 23 TWh ($7.8\ 10^7$ MMBtu). This number could be much higher if a solution for brine disposal in Southwest France were considered.

For Denmark, the evaluation is also based on the collection of worldwide salt deposits by [5]. The same approach is used with Denmark as for Germany and France to obtain the salt area in a 20 km (12 mi) wide corridor along the EHB (Figure 5).
The Permian salt (Zechstein) has the most extensive coverage. Above it, some Triassic formations (Keuper, Röt) are not included in the evaluation since constructing multiple caverns on top of each other is not a common practice.

Regarding brine disposal, the authors lack information about existing brine processing industries in Denmark. It is also unclear whether Danish legislation would permit brine discharge into the open sea. However, for comparison purposes with Germany and France, it is assumed that a similar percentage of the salt area (1% for Germany, 0.4% for France) could be utilized for constructing hydrogen storage caverns. The total salt area along the EHB in Denmark is 12,906 km² (4983 mi²), which is reduced to an estimated suitable area of 129 km² (50 mi²) or 52 km² (29 mi²) using the scaling factors derived for Germany or France, respectively. This translates to a hydrogen energy storage potential of 90 TWh ($3.1\ 10^8$ MMBtu) or 36 TWh ($1.3\ 10^8$ MMBtu), which is significantly higher than the anticipated storage demand of 0.7 TWh ($2.4\ 10^6$ MMBtu) by 2030 or 5.3 TWh ($1.8\ 10^7$ MMBtu) by 2050. It remains uncertain whether Denmark would develop a large number of new caverns, if the local storage demand would already be met.

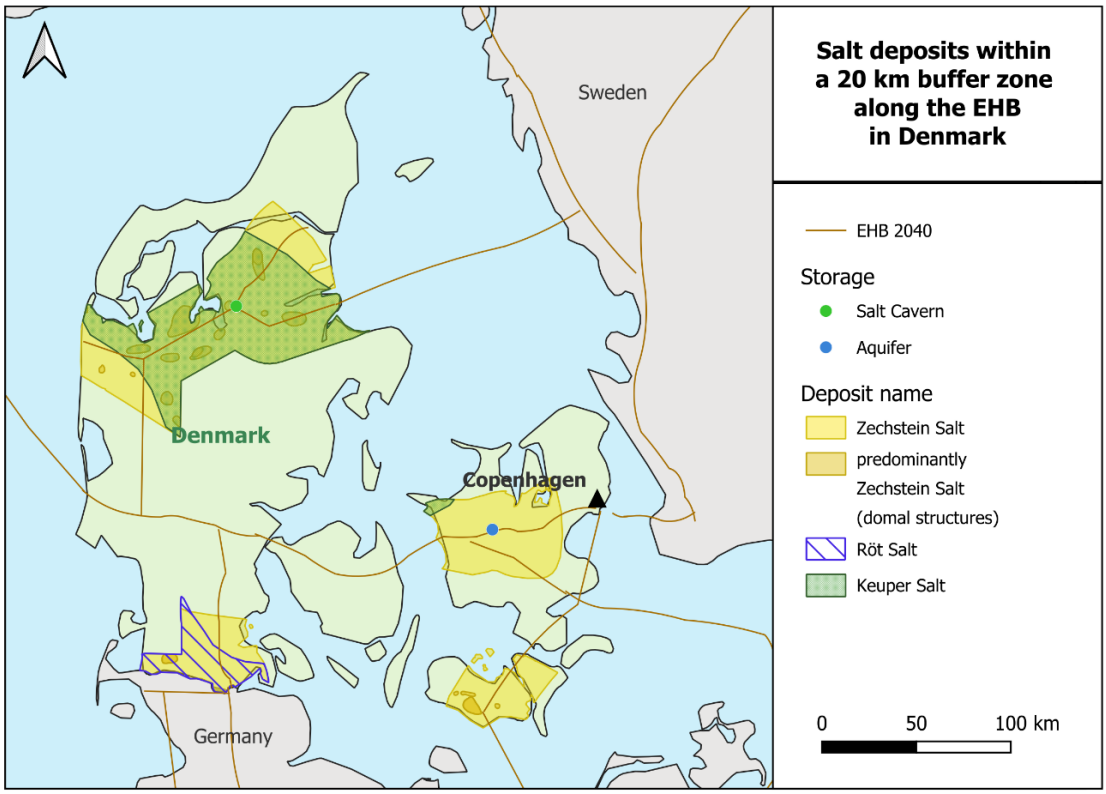

Figure 5. Salt structures in Denmark along the EHB corridor. This map was created based on data from [5,16].

As noted in sources [12-14], among the Benelux countries, only the Netherlands has salt structures suitable for constructing storage caverns. An analysis of the data shows that most of the existing salt structures are within the corridor along the EHB.

Using a similar evaluation method based on individual properties as applied in Germany, the Permian unit, as diapiric and pillow salt, shows a potential area of approximately 84 km² ($2.9\ 10^8$ MMBtu) near the planned EHB (2040). This could result in a hydrogen storage capacity of around 60 TWh ($2.0\ 10^8$ MMBtu) in the Netherlands (Table 3), assuming no additional restrictions are applied. Given the anticipated storage demand of 6.3 ($2.1\ 10^7$ MMBtu) TWh by 2030 and 31.6 TWh ($1.1\ 10^8$ MMBtu) by 2050 [6], it is debatable whether the development of over 400 new caverns would be necessary in the Netherlands.

The need to utilize the produced brine in industrial processes and the existing infrastructure may further limit this hydrogen storage potential. However, it is known that a well-developed brine pipeline infrastructure exists near the salt structures in the Netherlands.

The salt structures in the UK, as referenced in source [12], are situated predominantly along the EHB corridor (except the offshore structures in the Channel and the Irish Sea).

Table 3. Summary of salt area and application of constraints for each country. [1]without Aquitaine Basin and Muschelkalk

Country	Structure	Total salt area (EHB corridors) [km^2] ([mi^2])	Refined area (EHB corridors) [km^2] ([mi^2])	Refined area (EHB & brine disposal) [km^2] ([mi^2])	Potential caverns (EHB & brine disposal)	H2 storage potential (EHB & brine disposal) [TWh] ([MMBtu])
Germany	diapiric salt and layered salt	62 356 (24 073)	1 598 (617)	716 (276)	3 508	501 (1 709 478)
France	diapiric salt and layered salt	8 569 (3 308)		33 (13)	138	22.9 (78 144)
Denmark	diapiric salt and layered salt	12 906 (4 984)		52-130 (20-50)	254-635	36-90 (122 837-307 093)
Netherlands	diapiric salt and layered salt			84 (32)	413	59 (201 315)
United Kingdom	diapiric salt and layered salt		75 (29)		366	52 (177 431)

Using a similar evaluation method based on individual properties as applied in Germany, the Triassic unit in the UK is more extensive than the Permian unit, which ends in the northeast of the country. Both units present a potential area of approximately 75 km² (2.6 10^8 MMBtu) near the planned EHB (2040). This could translate to a hydrogen storage capacity of 52 TWh (1.8 10^8 MMBtu) in the UK, assuming no additional restrictions are applied.

However, issues related to infrastructure setup and brine disposal could potentially reduce this estimated hydrogen storage capacity, but these factors are beyond the scope of this evaluation.

7. Discussion

The potential for developing new salt cavern storages for hydrogen has been assessed for five European countries using literature data on the spatial distribution of salt formations and additional information regarding the suitability of these salt structures for cavern development. The areas identified for cavern development were then limited to the vicinity of the planned European Hydrogen Backbone (EHB) and, where applicable, to regions near brine discharge options (brine processing industry or open sea). Table 4 compares the resulting potentials with reference data on expected storage demand and the potential from converting natural gas storage caverns.

In Denmark, France, and Germany, extensive areas with existing salt structures were excluded from the evaluation because they are beyond the defined maximum distances to the EHB or brine disposal options. While these are not absolute limits, higher pipeline connection costs would impact the economic feasibility of developing storage in these areas, which is a critical factor for many storage development projects.

Table 4 clearly shows that converting natural gas storage caverns alone will not provide sufficient storage capacity to meet the demand for 2050. For 2030, converted natural gas caverns could cover a significant portion of the projected demand, but their availability is highly uncertain. Therefore,

developing new caverns for hydrogen storage will be essential to ensure adequate storage capacity for the future hydrogen market.

Table 4. Summary of hydrogen storage demand figures, storage potential from natural gas conversion (all from [6]) and new developed storage potential. Development of new caverns is restricted to a 20 km (12 mi) corridor along the EHB and up to 50 km (31 mi) from the nearest brine disposal point. *The figures for total Europe from [6] encompass all European countries with reported demand and gas storage, whereas the potential for new caverns only includes the five countries examined in this study.

Country	**Hydrogen storage demand 2030 [TWh] ([MMBtu])**	**Hydrogen storage demand 2050 [TWh] ([MMBtu])**	**Hydrogen storage potential (converted natural gas caverns) [TWh] ([MMBtu])**	**Hydrogen storage potential (new developed) [TWh] ([MMBtu])**
Denmark	0.7 (2 388)	5.3 (18 085)	1.3 (4 436)	36 (122 837)
France	8.2 (27 977)	43.1 (147 206)	2.5 (8 530)	23 (78 144)
Germany	15.9 (54 308)	111.4 (380 086)	39.5 (134 867)	501 (1 709 478)
Netherlands	6.3 (21 496)	31.6 (107 833)	0.9 (3 071)	59 (201 315)
United Kingdom	6.9 (23 559)	57.9 (197 558)	3.7 (12 617)	52 (177 431)
Europe (total)*	**72.2 (246 674)**	**466.4 (1 591 674)**	**50 (170 607)**	**>671 (>2 289 205)**

8. Conclusion

For most countries investigated, the identified potential for new caverns is comparable to or even exceeds the projected storage demand for 2050 [6]. The combined potential of the five countries could be sufficient to meet the demand for all of Europe. However, the identified potential is similar to the projected demand, meaning that a substantial portion of the identified areas must be utilized for hydrogen storage caverns, requiring the construction of thousands of new caverns.

It is important to note that the evaluations in this work are theoretical and cannot replace individual feasibility studies for each site considered for storage development. Although the authors adopted a conservative approach regarding the usability of the identified salt areas for cavern development, site-specific factors (e.g., salt quality or land use conflicts) may not be fully accounted for in the applied reduction factors. These factors would typically reduce the storage potential rather than increase it.

It is worth remembering that the use of salt caverns for gas storage in Europe began in the 1970s, and it took several decades to develop the current storage capacities (244 TWh ($8.3\ 10^8$ MMBtu) of natural gas in the EU and UK, corresponding to approximately 50 TWh ($1.7\ 10^8$ MMBtu) of hydrogen storage capacity [6,17]). Now, the storage industry faces the challenge of developing nine times this capacity within 25 years. Given that the timeline for developing new cavern storage is around 10 years [18] and that only 9.1 TWh ($3.1\ 10^7$ MMBtu) are already announced in Europe for 2030 [18], a significant shortage of hydrogen storage capacities may arise in the next decade. Besides geological storage potential, factors such as the timeline for investment decisions and authority approvals, the availability of certified materials and personnel for storage planning and construction, and brine disposal capacities across Europe could limit the provision of hydrogen storage capacities. This situation will likely affect market development and prices for hydrogen and storage capacities.

Furthermore, in this work no significant differences were identified between the dimensioning of storage caverns or sites for natural gas and hydrogen. Generally, it seems advantageous to opt for large cavern volumes and depths, subject to geological and technical constraints.

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References

[1] Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee ant the Committee of the Regions: A hydrogen strategy for a climate-neutral Europe; Bussels, 08/07/2020.
[2] Axelera: HyPSTER, 1st demonstrator for green hydrogen storage; https://hypster-project.eu/ (retrieved 20/03/2025).
[3] Grange, M.; Hevin, G.; Djizanne, H. (2023): HyPSTER: 1st Demonstrator for Green Hydrogen Storage in France; SMRI Fall 2023 Technical Conference, 2-3 October 2023 San Antonio, Texas, USA
[4] Djizanne, H.; Prats, F.; Murillo, C.; Pique, S.; Hevin, G.: Risk Assessment for Hydrogen Storage in Salt Cavern; SMRI Fall 2024 Technical Conference, 22-25 September 2024 Edmonton, Alberta, Canada
[5] Horvath, P.L.; Miau, S.; Schneider, G.; Bernhardt, H.; Weiler, C.; Bödeker, J.; Wippich, M. Tangermann, T.; Ratigan, J. (2018): Update of SMRI's Compilation of Worldwide Salt Deposits and Salt Cavern Fields; SMRI Research Report.
[6] Cihlar, J.; Mavins, D.; van der Leun, K. (2021): Picturing the value of underground gas storage to the European hydrogen system, Guidehouse.
[7] Grünpapier Wasserstoffspeicher; Bundesministerium für Wirtschaft und Klimaschutz der Bundesrepublik Deutschland (2023).
[8] Frontier Economics Ltd.: Why European Underground Hydrogen Storage Needs Should Be Fulfilled; (2024).
[9] BGR: Salt structures of northern Germany; Federal Institute for Geosciences and Natural Resources (BGR, 2024); BGR Geoportal - Geoviewer (map, retrieved 04/03/2024).
[10] Von Goerne, G.; Fleig, S.; Rohkar, R.; Donadei, S. (2016): Informationssystem Salzstrukturen: Planungsgrundlagen, Auswahlkriterien und Potentialabschätzung für die Errichtung von Salzkavernen zur Speicherung von Erneuerbaren Energien (Wasserstoff und Druckluft); InSpEE - Sachbericht 03ESP323B.
[11] Donadei, S.; Röhling, S.; Fleig, S.; Zapf, D.; Horvath, P. L. (2020): Informationssystem Salz: Planungsgrundlagen, Auswahlkriterien und Potenzialabschätzung für die Errichtung von Salzkavernen zur Speicherung von Erneuerbaren Energien (Wasserstoff und Druckluft)– Doppelsalinare und flach lagernde Salzschichten; InSpEE-DS - Sachbericht 03ET6062A.
[12] Bannach, A.; Klafki, M.; Bleschert, K.-H.; Piske, A. (2005): Speicher-Standortstudie für Niederland und Großbritannien. - Studie für RWE Energy AG, ESK GmbH.
[13] Duin, E.J.T.; Doornenbal, J.C.; Rijkers, R.H.B.; Verbeek, J.W.; Wong, Th.E. (2006): Subsurface structure of the Netherlands - results of recent onshore and offshore mapping; Netherlands Journal of Geosciences - Geologie en Mijnbouw /85-4/245-276/2006.
[14] Doornenbal, J.C.; Pagnier, H.J.M. (2004): Geological Atlas of the Subsurface of the Netherlands – onshore; Netherlands Institute of Applied Geoscience TNO; nlog.nl (retrieved 11/03/2024).
[15] Louvet, F.; Charnavel, Y.; Hévin, G. (2017): Thermodynamic Studies of Hydrogen Storage in Salt Caverns; SMRI Spring 2017 Technical Conference, 23 – 26 April, 2017 Albuquerque, New Mexico, USA.
[16] EHB: European Hydrogen Backbone (https://www.ehb.eu/) (retrieved 04/04/2024).
[17] GIE (Gas Infrastructure Europe): Gas Infrastructure Europe Map – GIE Storage Map 2021 (https://www.gie.eu/) (retrieved 04/04/2024).
[18] Peterse, J.; Kühnen, L.; Lönnberg, H. (2024): The role of underground hydrogen storage in Europe; Guidehouse.