OVERVIEW OF BEST SUITED CAVERN CONFIGURATIONS FOR SPECIFIC HYDROGEN STORAGE DEMAND FIGURES

HYPSTER PROJECT

Deliverable 2.9

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1. INTRODUCTION

The HyPSTER project is the first EU-funded demonstrator for hydrogen storage in salt caverns. Among other work, the project investigates using simulation tools to model and optimize the design and development of hydrogen storage facilities in salt caverns. These tools can evaluate the technical and commercial aspects of various plant configurations.

In addition to preparing the demonstration of storing hydrogen in salt caverns at the site Étrez, France, the project is also meant to facilitate the replication of the technology in other locations around Europe. In previous steps representative cavern configurations, geological properties and exemplary operating cycles have been developed and published [1,2]. Further work included a sensitivity analysis of the storage capacity with respect to the different cavern properties. These results are summarized in the present work (section 4).

The next step for assessing the replicability of the cavern storage technology is to investigate the availability of suited salt structures for cavern development. Several publications exist on the occurrence of salt deposits through Europe, these usually only cover single regions or locations. The work of Horvath et al. [3] is one of the few comprehensive collections of salt data worldwide and will be used of the present evaluations. This work will address the question, which fraction of the overall salt deposits can be assumed to be suited for the development of hydrogen storage sites. This will cover aspects of infrastructure development (distances to the hydrogen backbone and to brine disposal options) as well as properties of the salt structures.

Based on assumptions for a standard cavern and for the distances between caverns the storage potential for hydrogen in the vicinity of the European Hydrogen Backbone (EHB) and to the options for brine disposal has been derived. These values are further compared to the expected hydrogen storage demand and to the existing storage capacities for natural gas. Furthermore, the challenges regarding the timeline for hydrogen storage development in comparison to historical development of the natural gas storage caverns are commented.

2. HYDROGEN STORAGE DEMAND FIGURES

In a very detailed study from 2021 by the consultant Guidehouse for the association Gas Infrastructure Europe (GIE) [4], the expected hydrogen storage demand for Europe was evaluated with 72 TWh for 2030 and 466 TWh for 2050. For Germany this study specifies 16 TWh for 2030 and 111 TWh for 2050, which is in comparison to the recent green paper of the German Ministry for Economics and Climate Protection [5] (2 TWh for 2030, 74 TWh for 2045) notably higher. In another recent study by the consulting companies Artelys and Frontier Economics for GIE [6] the total demand for hydrogen storage in Europe is specified as 45 TWh for 2030 and 270 TWh for 2050 (both based on the lower heating value), which is approximately 40% lower than earlier study by Guidehouse for GIE [4].
As all these numbers are based on models and assumptions, they naturally have a very high level of uncertainty. For the present work the numbers from [4] will be used for comparison with the geological potential, even though they might overestimate the actual storage demand. But they have the advantage to allow a country specific comparison. Table 2.1 provides an overview of the given storage demand figures for Germany, France, Denmark, the United Kingdom and the Netherlands, which are the countries in Europe best known for their salt cavern potential.

TABLE 2.1: Overview of hydrogen demand and hydrogen storage demand in selected European countries (reproduced from [4]).

Country	**Hydrogen demand 2030 [TWh]**	**Hydrogen demand 2050 [TWh]**	**Hydrogen storage demand 2030 [TWh]**	**Hydrogen storage demand 2050 [TWh]**
Denmark	3.1	22.3	0.7	5.3
France	34.7	182.1	8.2	43.1
Germany	66.9	470	15.9	111.4
Netherlands	26.6	133.4	6.3	31.6
United Kingdom	29.1	244.2	6.9	57.9
Europe (others)	144,1	916,1	36,9	212,2
Europe (total)	**304.5**	**1 968.1**	**72.2**	**466.4**

3. GEOLOGICAL POTENTIAL FOR HYDROGEN STORAGE IN SALT CAVERNS

The geological potential for hydrogen caverns in salt formations holds significant promise as a crucial component of the transition towards a sustainable energy future. Salt formations, particularly those with halite content, offer ideal conditions for the creation of underground storage facilities for hydrogen gas.

Salt formations possess unique properties that make them well-suited for cavern storage. Their impermeable nature ensures minimal leakage, providing a secure containment environment for hydrogen gas, which is known for its low molecular weight and propensity for diffusion. Additionally, the self-healing capabilities of salt formations further enhance the integrity of these storage facilities, minimizing 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 adaptation of storage capacity to meet fluctuating demand for hydrogen.

Furthermore, salt formations often occur at considerable depths beneath the Earth's surface, providing ample space for the construction of large-scale storage facilities without occupying valuable land surface. This depth also offers natural insulation, maintaining stable temperature conditions conducive to the safe storage of hydrogen gas.

An extensive compilation of salt deposits worldwide is provided by the work of Horvath et al. [3]. It has the advantage to offer spatial resolved data on the occurrence of salt. However, it has the disadvantage of providing only rough information about the depth, thickness and quality of the salt. In the present work it is used for a preliminary evaluation of the geological potential in Germany, France and Denmark. For Germany and France, this is followed by an evaluation of additional references. The appropriate salt deposits of Germany were further evaluated using geological data from the Federal Institute for Geosciences and Natural Resources [7] as well as the results of the research project InSpEE and InSpEE-DS [8,9]. However, in these references it is assumed that caverns can always be positioned in a dense hexagonal packing resulting in at least 11 caverns per 1 km^2 (depending on the required safety distances), which is a very optimistic approach (see section 5).

Information on salt deposits for the Benelux-countries have been reviewed. Only the Netherlands was found to have relevant salt deposits [10-12].

The geological data for the UK was retrieved mainly from [3] and [10].

4. INDUSTRIAL-SCALE CAVERN CONFIGURATIONS

In a previous part of the project HyPSTER the relevant cavern configurations for hydrogen storage in Europe have been identified [1], a basic description of relevant salt properties has been given [2] and the effects on the long-term storage performance has been investigated. A summary of these results is shown below. Table 4.1 lists the main parameters of typical industrial scale caverns and examples, where similar caverns can be found. Additional investigated properties comprise the salt creep rates (case 8 – 10), the injection temperature (case 11), the diameter of the tubing of the access well (case 12), the heat transfer coefficient between the cavern inventory and the surrounding salt rock (case 13) and the type of inventory (hydrogen vs. natural gas, case 16).

TABLE 4.1: Definition of industrial-scale caverns – Variation of the main parameters [1].

Parameter	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**	**Case 7**
Depth of last cemented casing shoe [m]	600	900	900	900	1 400	1 400	1 400
Geometrical cavern volume [m^3]	350 000	200 000	500 000	800 000	200 000	500 000	800 000
Cavern height (roof to sump) [m]	70	70	140	300	70	140	300
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

To investigate the long-term behavior of the caverns a simple operating schedule is applied based on an average load cycle for each common year, that is scaled to almost the full operating pressure range for each leap year. In Figure 4.1 this operating schedule is illustrated as the relative well head pressure over time. This relative well head pressure represents the pressure spread of each cavern between its individual maximum and minimum operating pressure (which mainly depend on the casing shoe depth and have to be assessed specifically for any real cavern in a geomechanical study).

Furthermore, two scenarios are investigated describing the withdrawal and injection of hydrogen with 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 and < 20 m/s, case 14, or +/- 20 bar/day and unlimited velocity, case 15).

Regardless of the type of storage inventory salt caverns converge with time due to salt creep. Therefore, the cavern volume decreases with time. Typical creep closure rates (volume loss rates) could range from 0.05 %/year (shallow caverns) to 1 %/year (deeper caverns). These numbers depend strongly on the rock parameters and the operational cycles, and values beyond this range have been observed in some instances. Furthermore, creep closure is typically higher in the first years of operation due to the stronger influence of the transient creep.

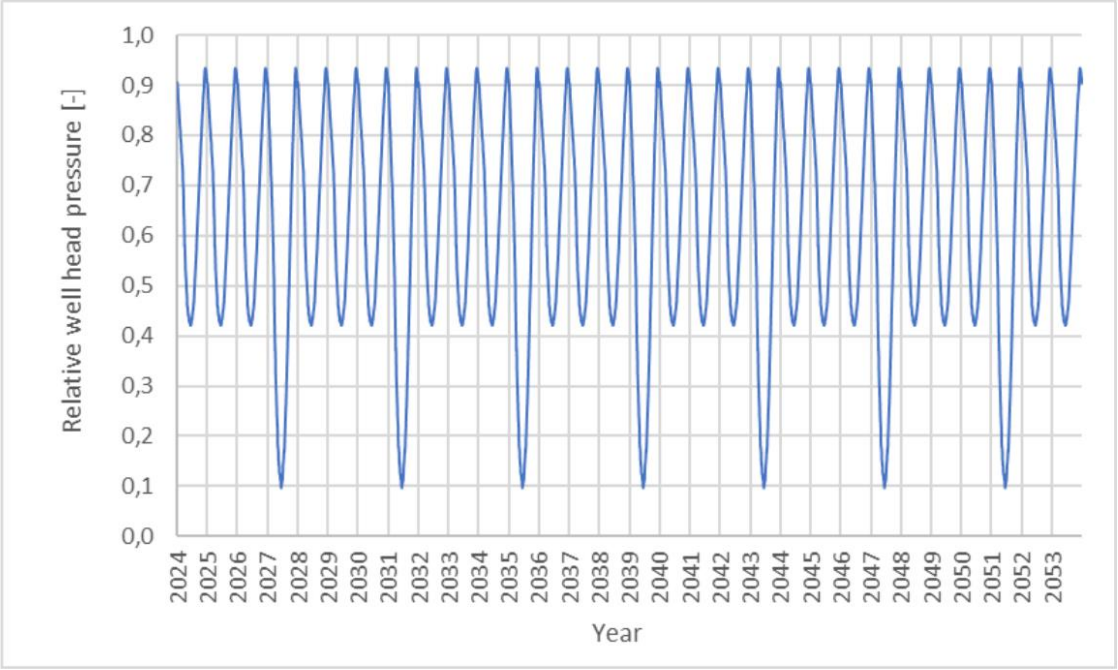


Figure 4.1: Definition of the industrial scale operating schedule starting with the 1st of October 2024.

The mentioned effects have been reproduced in the modeling of the cavern cases over 30 years of operation. For most cases the yearly cavern volume loss stayed below 1 %/year, because relative well head pressures below 0.4 are only reached every fourth year. Only for the case of a deep cavern (casing shoe at 1 400 m) in a very creep-prone salt a yearly cavern volume loss of 2.5 %/year was obtained.

The modeling of the various cases confirmed that the long-term development of the cavern volume is dominated by the static creep behavior. This can simplify the choice of the applied creep model and software for the predictive modeling of storage capacities and performance (see [2] for more details about the geomechanical modeling).

The analysis of the modeled cases revealed that the hydrogen storage capacity is roughly proportional to the cavern volume and the depth of the last cemented casing shoe and could be simplified with acceptable accuracy by an average specific energy storage capacity of 0.27 kWh/m^3/m (lower heating value, see Figure 4.2). The actual capacity of the modeled cavern could then be obtained by multiplying this specific value with the spatial cavern volume and the depth of its last cemented casing shoe. The deviations from this average value are due to thermal effects and the real gas behavior of hydrogen. It should also be noted that the operating pressure range of the cavern has been strongly simplified in the analysis and can have a significant effect for a real cavern depending on the local geology.

These findings indicate that the optimization of the storage capacity of a salt cavern is mainly a question of choosing the optimal cavern volume and depth. Of course, both are strongly limited by the local properties of the salt formation and need to be addressed individually for each location. Other important aspects are the costs associated with the chosen configuration. There are usually fixed costs for the development of a site and for the drilling of each well and additional cost components more or less proportional to the cavern volume and the depth of the casing shoe. So, for minimizing the impact of the fixed costs, both volume and depth should be chosen as large or deep as possible with respect to the geological limitations. However, for casing shoe depths significantly below 1 500 m, the costs for the well start to grow more than proportional due to technical challenges with the increasing pressure ratings, which also have to be assessed individually for each well. In general, these considerations are similar to the development of a natural gas storage site. In the present work no significant differences could be identified between the dimensioning of storage caverns or sites for natural gas or hydrogen.

The cavern performance modeling showed that with the given configuration (corresponding to case 3, maximum pressure of 165 bar, minimum pressure of 60 bar and a 7” tubing) the flow velocities in the tubing during withdrawal at 20 bar/day would almost reach a maximum of 200 m/s, which is not considered realistic. Injection in this case would reach a maximum of 70 m/s, which is still very high. If the flow velocities are capped by 20 m/s, this cavern can be emptied and filled (i.e. ramping down and up between maximum and minimum pressure) within approximately 14 days each.

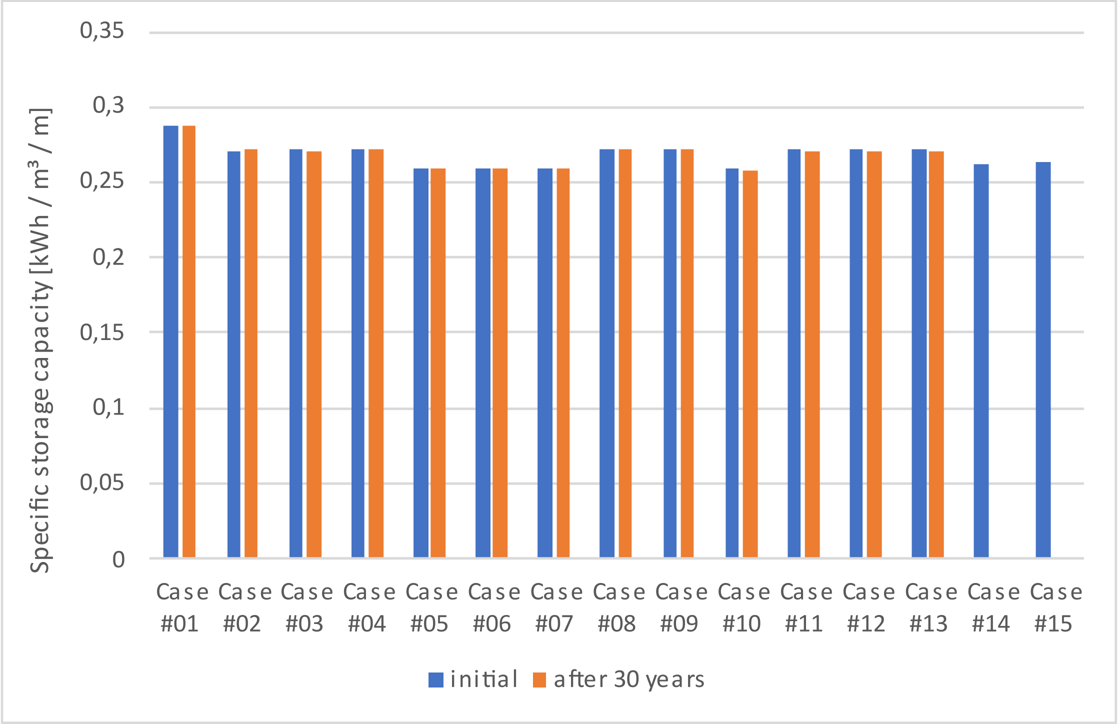


Figure 4.2: Specific energy storage capacity (lower heating value) of the modeled cavern configurations at beginning and end of the 30 years modeling period.

The comparison with natural gas (case 16) shows the great difference of the energy content that can be stored in a salt cavern with both types of fuel. On a molecular basis about 55 % more natural gas can be stored and withdrawn from the investigated cavern than hydrogen, mainly due to the different compressibility of the gases. Regarding the energy content the cavern filled with natural gas can store and release approximately 5 times as much energy as the cavern filled with hydrogen due to the additional difference of the heating values. It should be noted that this factor depends on the applied boundary conditions (e.g. operating pressure range), in other thermodynamic studies it is assumed to lay between 4 and 4,5 [13].

According to [4] the demand for hydrogen storage in Europe (including UK) will be 72 TWh in 2030 and 466 TWh in 2050, while the current storage capacity for natural gas in salt caverns is 244 TWh. 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 of hydrogen storage capacity. So, even under the highly optimistic assumption that all natural gas storages could be converted to hydrogen until 2030, this still would not suffice to meet the projected demand. Realistically, a major part of the existing natural gas storages will still be required in 2030 and are not available for conversion to hydrogen. So, building new storages is the only way to approach any of the projected hydrogen storage demand figures [4-6].

5. ACCESSIBLE HYDROGEN STORAGE POTENTIAL IN VARIOUS EUROPEAN COUNTRIES

Even though the geological potential for the creation of salt caverns for hydrogen storage in Europe is abundant, not all this potential can be easily realized technically and economically. Two important aspects limiting the overall feasibility of storage cavern construction are the distance between the storage site and the location of hydrogen production and consumption and the distance between the storage site and a suitable site for brine discharge. To assess both aspects in a general way some simplifications had to be made. The distance to the hydrogen production and consumption is represented by the distance to the next section of the planned European Hydrogen Backbone (EHB) [14], which is meant to connect the main centers for hydrogen production and consumption in Europe until 2040 or earlier. A maximum of 20 km between a salt formation and the EHB is applied as cut-off criterion for the length of the required high-pressure hydrogen access pipeline.

Assessing the feasibility of brine discharge is a complex issue that strongly depends on the applicable national legislation. It was evaluated in detail for the situation in Germany. For the other investigated countries scaling factors have been applied in analogy.

The reference literature of the salt structures is given in chapter 3. In several cases the available literature data is not sufficient to fully evaluate the geological potential in terms of salt thickness, depth and quality. In these cases scaling factors based on the lateral extent of the salt formations have been applied to achieve at least a rough estimate of the geological potential.

The evaluation of the area of the salt structures that meet the mentioned conditions, was used to calculate the possible hydrogen energy content in potential caverns which could be built there. The approach used was that for an area of 1 km² possibly 7 standard caverns (500 000 m³ spatial volume, casing shoe at 1 000 m) could be build which equals a hydrogen energy content of about 1 TWh (lower heating value). To consider necessary cavern distances and therefore not usable space a reduction ratio of 0,7 was applied (a comparable approach was taken in [8]).

The chosen approach is a strong simplification compared to typical feasibility studies, and the results obtained do not mean, that locations outside of the identified areas cannot be developed commercially. It mainly reflects the tendency that larger distances to the hydrogen grid and to the brine disposal put a burden on the profitability of storage development making its commercial feasibility less likely.

5.1. Germany

The most encompassing overview of salt structures worldwide is provided by [3]. This database is used to illustrate salt formations in a corridor of 20 km left and right of the planned EHB in Germany (Fig. 5.1).

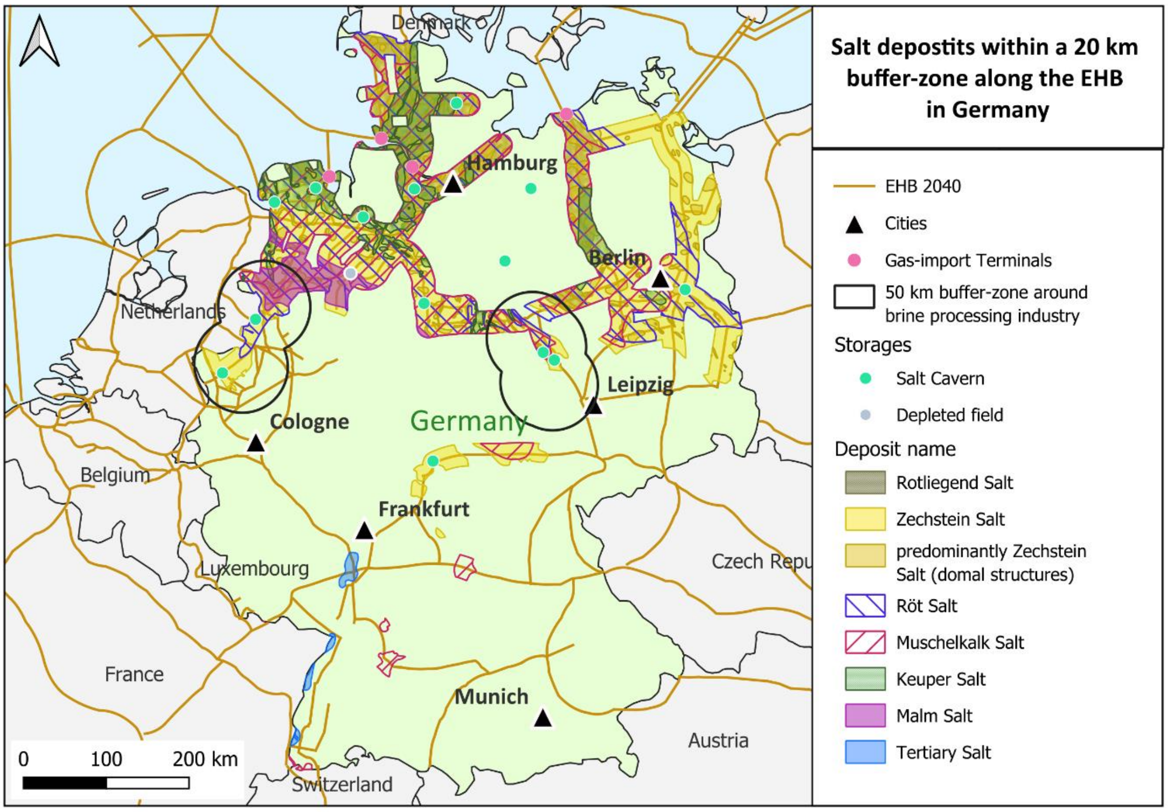


Figure 5.1: Salt structures in Germany [3] in the vicinity of the EHB (2040) [14].

When the area of these salt structures is used to calculate the hydrogen storage potential (Table 5.1), very large numbers of more than 60 000 km² are obtained, which are not realistic due to several technical limitations (e.g. thickness and depth of salt formation, existing buildings and infrastructure on the surface etc.).

As an alternative reference for Germany, which takes these factors into account, the maps from [8,9] can be used. These maps have been created based on a detailed analysis of salt structures in Germany, that fulfil specific criteria for the salt thickness and depth as well as salt quality, distances to faults or concurring salt usage and surface structures. The structures derived from [8,9] have been cross-checked with own data for each location. A salt thickness of at least 300 m as well as a sufficient depth of 400 m – 2000 m below ground level have been chosen as criteria for the inclusion of the given salt structure. Figure 5.2 provides an overlay of the suited salt structures according to [9] and the corridors 20 km left and right along the EHB.

Comparing Figures 5.1 and 5.2, it is obvious that the area of salt suited for cavern construction along the EHB is significantly smaller than the total area of the salt structures from [3]. This is reflected in Table 5.1, where the total area of the suited structures is also specified.

The evaluations above do not include potential restrictions due to the necessary disposal of the brine produced during cavern leaching. This can be a highly challenging aspect during cavern construction with a potential to incur prohibitively high costs, if no brine discharge options can be identified in the vicinity of a planned storage site. The offtake of the brine by the chemical industry is regarded as the most feasible option for salt cavern leaching and, often, brine processing industry has developed in the past around sites with historical salt production and leaching activities. Today, seven brine processing industry sites in Germany are known to the authors (Bernburg, Borth, Epe, Rheinberg, Schkopau, Stassfurt and Teutschenthal). As brine can be transported to the industrial sites via low-pressure product pipelines, a maximum distance of 50 km is considered feasible in the present work. These distances around the known industry sites are indicated in Figure 5.1 and Figure 5.3.

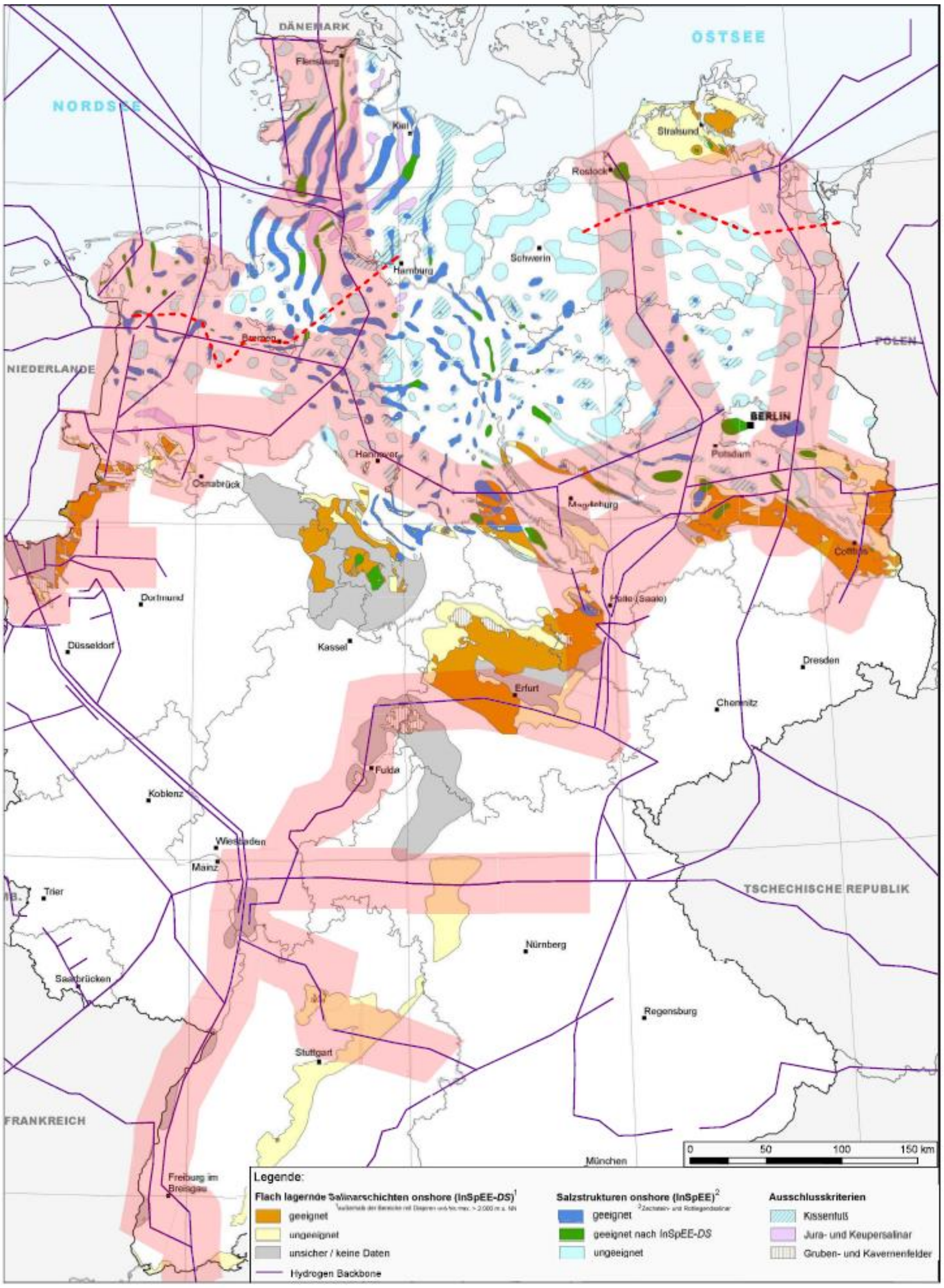
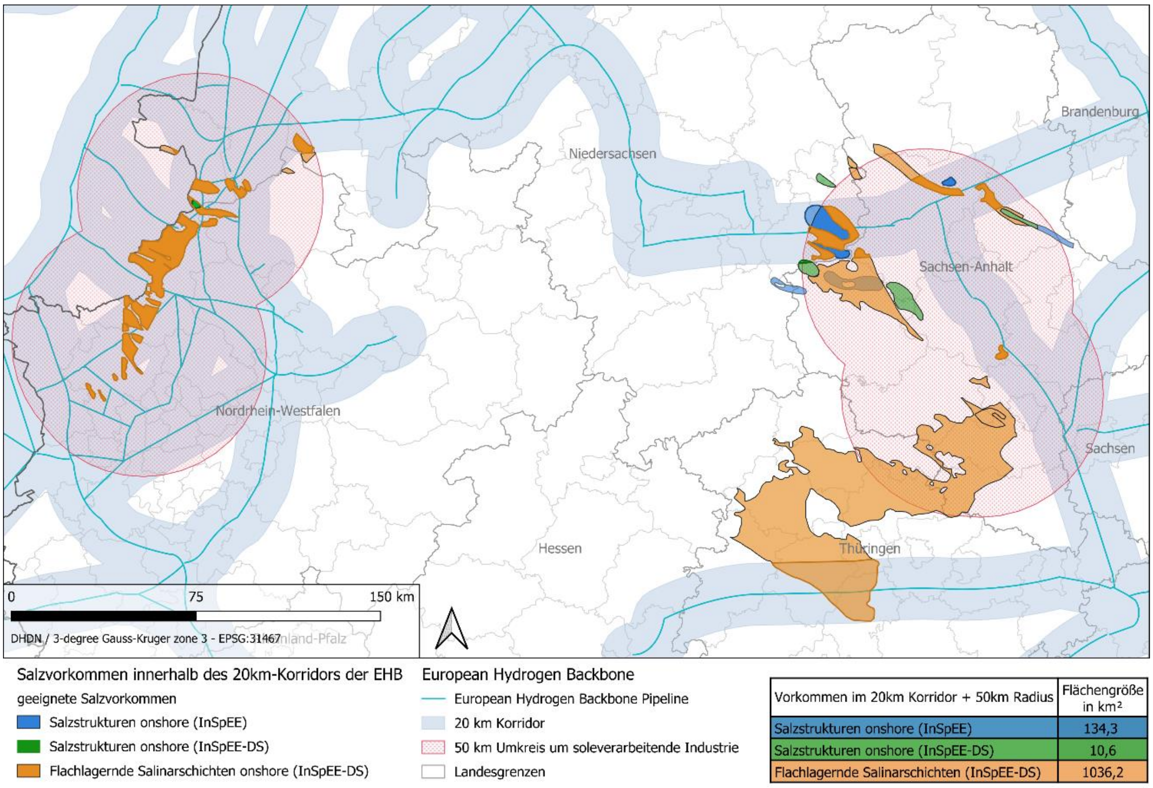


Figure 5.2: Salt structures suited for hydrogen storage in Germany (reproduced and altered from [9]) with the corridors 20 km left and right of the EHB [14].



Vorkommen im 20km Korridor + 50km Radius	Flächengröße in km²
Salzstrukturen onshore (InSpEE)	134,3
Salzstrukturen onshore (InSpEE-DS)	10,6
Flachlagernde Salinarschichten (InSpEE-DS)	1036,2

Figure 5.3: Suited salt structures in Germany (redrawn from [9]) next to the existing brine processing industry (50 km) and 20 km corridors along the EHB [14].

An alternative option for brine disposal can be the discharge into the open sea, which is practiced in a few locations at the German North Sea coast. For the present work it should be assumed that this could also be practiced for new hydrogen storage sites along the total German shoreline (in reality, this would be subject to approval by the competent authorities). The resulting area within 50 km of the German coast and with a maximum distance of 20 km to the EHB is indicated as a shaded area in Figure 5.4.

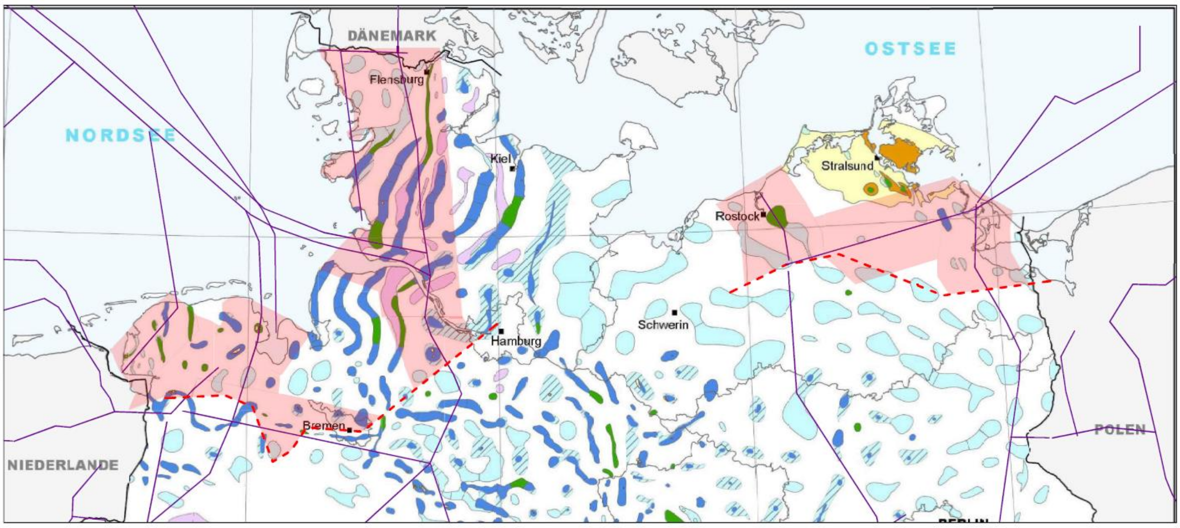


Figure 5.4: Suited salt structures in Germany (reproduced and altered from [9]) with the combined area of the corridors 20 km left and right of the EHB [14] and a maximum distance of 50 km from the German coast.

Considering the options for brine disposal significantly reduces the feasible salt structures for the development of new cavern storages (Table 5.1). A total area of 716 km² was identified, whereof the majority is Zechstein salt (mainly diapirs) along the coast (571 km²). This is still approximately half of the identified suited area along the EHB. A smaller fraction of 145 km² are inland Zechstein diapirs next to the brine processing industry. In principle, there is also an additional potential of 1.036 km² of bedded salt in the vicinity of the brine processing industry. However, the availability of geological data for these locations is limited incurring significant uncertainty about the geological and economic feasibility for cavern construction in these areas.

Additional salt deposits may exist in several areas (e.g. Triassic/Jurassic), but are neglected in this evaluation, because they are located directly above the Zechstein salt and the construction of multiple caverns on top of each other is not commonly practiced in cavern industry. Other salt formations neglected in this evaluation are Tertiary deposits in the Upper Rhine Region. Because these are far from the identified brine disposal options, they could only be realized, if alternative options for brine disposal can be found.

Table 5.1: Potential of storage caverns and H2-energy content close to the EHB in Germany. *Additional potential in shallow bedded salt is specified in [9] for locations next to the brine processing industry, but is considered unsecure due to limited availability of geological data.

Stratigraphical Unit	**Structure**	**Total salt area (EHB corridors) [km^2]**	**Refined area (EHB corridors) [km^2]**	**Refined area (EHB & brine disposal) [km^2]**	**Potential caverns (EHB & brine disposal)**	**H2 storage potential (EHB & brine disposal) [TWh]**
Permian (Zechstein/Rotlieg.)	diapiric salt and layered salt	62 356	1 598	716 (1 036*)	3 508	501
Tertiary	diapiric salt and layered salt	883	16	-	-	-

Thus, considering the distances to the EHB and to the potential brine disposal a total energy storage capacity of 501 TWh was identified for Germany. This is significantly smaller than the potential identified in [8,9], where no filtering regarding the distances to the EHB or brine disposal had been applied and the caverns had been placed in a much denser hexagonal packing.

Looking at the existing cavern storage possibilities in Germany yields an amount of natural gas storage capacity of 165 TWh [15]. This amount of energy is stored in about 250 caverns. If one would substitute all natural gas by hydrogen an energy amount of 39.6 TWh [4] could theoretical be stored in these existing caverns (without consideration of potential technical limitations for cavern conversion). The potential of hydrogen storage in further developed brownfields accounts for about 160 TWh using the geology of the salt structures at the storage sites and the same calculation process.

In order to compare these numbers with the situation in other countries, scaling factors have been derived. A factor of 0.0256 is obtained as the ratio of the refined area and the total area along the EHB corridors. Considering the brine disposal results in an additional reduction of the refined area by a factor of 0.45. Thus, the area of the salt structures that is effectively used for cavern construction, corresponds to approximately 1 % of the total area of the salt structures along the EHB.

5.2. France

For France the evaluation was also started based on the compilation of worldwide salt deposits in [3]. Similar to the initial evaluation for Germany, only salt structures with a maximum distance of 20 km to the EHB [14] have been cut out. The resulting structures are illustrated in Figure 5.5. In Table 5.2 the resulting areas (total salt area) are given.

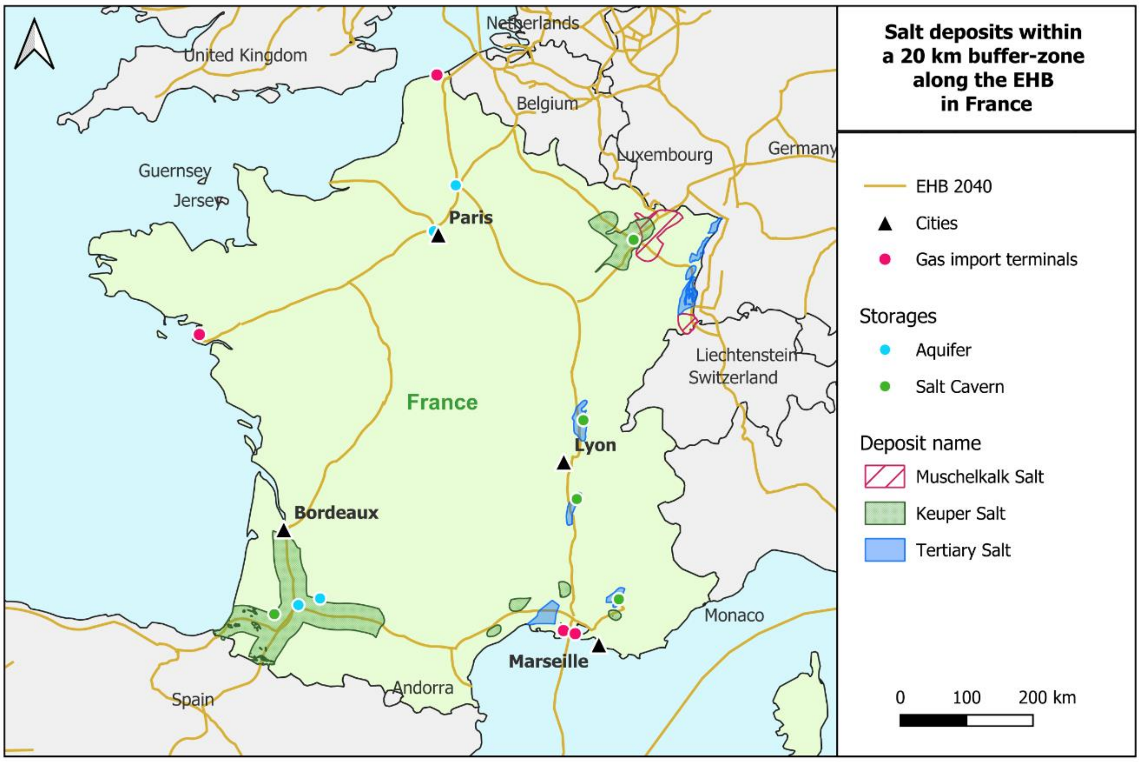


Figure 5.5: Salt structures in France [3] in the vicinity of the EHB (2040) [14].

The largest areas with salt structures close to the planned pipelines are comprised of the three regions:

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

This identified structures are well separated from each other, there is almost no overlap (except for some overlap of Muschelkalk/Keuper in Eastern France).

Unfortunately, there is little information about geological details publicly available, which makes it difficult to assess the feasibility of cavern construction in the specified areas. However, the results of an internal analysis of Storengy have been shared including the potential numbers of caverns in each location and the hydrogen storage potential (Table 5.2). This analysis does not include any new salt caverns in the Southwest of France due to lacking brine discharge options (too low acceptability for brine discharge into the open sea or capacity of brine processing industry). Furthermore, the development of the EHB is considered to have a lower priority in this region than in eastern France.

It seems that potential of brine disposal in north of Switzerland near the boundary with France and not far from the Jura Basin salt, but the lack of information make this option too uncertain today.

To make these results comparable to other countries, the required area of the salt structure has been back-calculated from the number of caverns based on the same assumptions as defined above (Table 5.2). Comparing this required area to the total salt area of the corresponding structures in the vicinity of the EHB yields a fraction of 0.4 % of the total area, that could realistically be used for cavern construction.

TABLE 5.2: Potential of storage caverns and H2-energy content close to the EHB in France.

Stratigraphical Unit (Geological Division)	**Structure**	**Total salt area (EHB corridors) [km^2]**	**Required area [km^2]**	**Potential caverns (EHB & brine disposal)**	**H2 storage potential (EHB & brine disposal) [TWh]**
Upper Triassic (Keuper, Carnian) (Aquitaine Basin)	bedded, domal	15 515	-	-	-
Lower Tertiary (Oligocene/Aquitanien) (Camargue Basin)	bedded, tectonized	905.84	-	-	-
Middle Triassic (Muschelkalk, Late Anisian) (Central European, Paris, Bresse-Jura Bas.)	bedded	3 559	-	-	-
Lower Tertiary (Oligocene) (Forcalquier Basin)	bedded, folded	425	1.7	7	1.24
Upper Triassic (Keuper, Carnian) (East of Paris Basin)	bedded	5 217	4.8	20	0.2
Lower Tertiary (Eocene-Oligocene) (Rhine Graben in Alsace-Jura Basin)	bedded, domal	1 552	9.5	40	10
Lower Tertiary (Eocene-Oligocene) (Rhone Graben)	bedded	489	1.4	6	1.2
Lower Tertiary (Eocene-Oligocene) (Bresse Basin)	bedded	886	15.5	65	10.25
France (total)		***28 915***	***33***	***138***	***22.9***

According to this evaluation considering the brine discharge options, the total hydrogen storage potential in the vicinity of the EHB in France is approximately 23 TWh. This number could probably be significantly higher, if a solution for brine discharge in the southwest of France was found.

5.3. Denmark

The evaluation for Denmark is also based on the collection of worldwide salt deposits [3]. The same approach as for Germany and France is used to obtain the salt area in a 20 km wide corridor along the EHB [14]. The results are illustrated in Figure 5.6 and Table 5.3.

The Permian salt (Zechstein) shows the largest extend. On top of it, there are partially Triassic formations (Keuper, Röt). These are not further considered in the evaluation because it is not common practice to construct multiple caverns on top of each other.

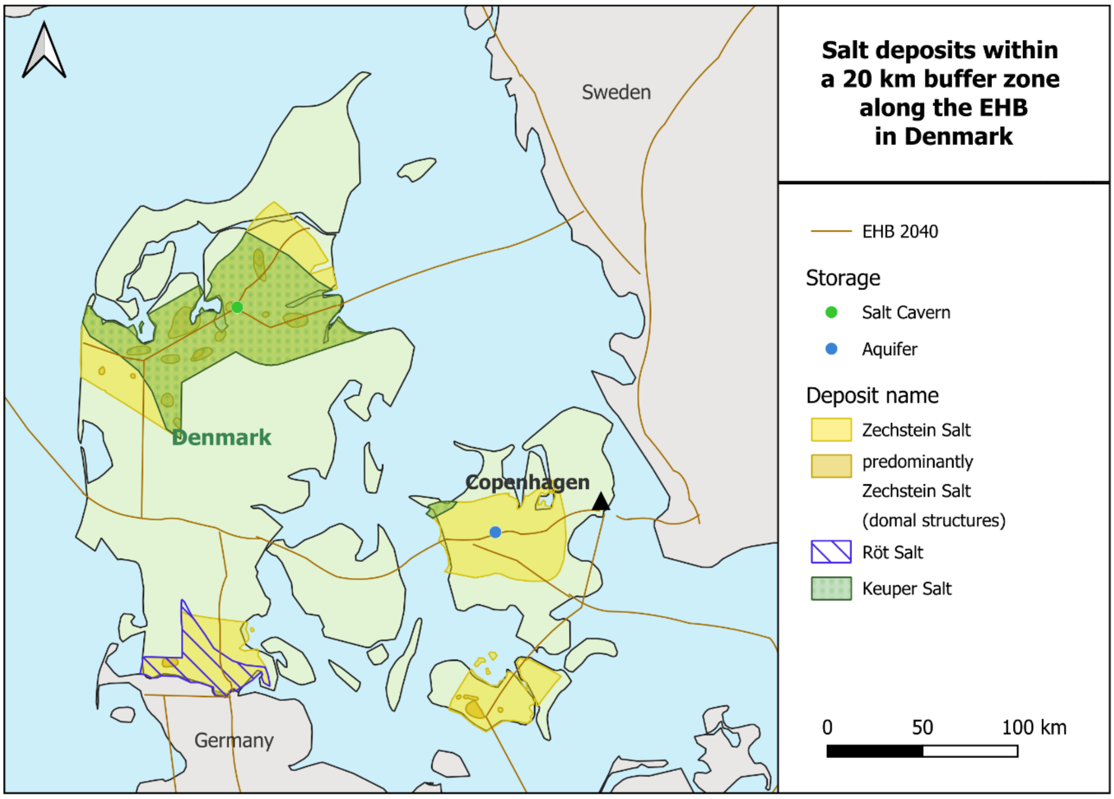


Figure 5.6: Salt structures in Denmark [3] in the vicinity of the EHB (2040) [14].

TABLE 5.3: Potential of storage caverns and H2-energy content close to the EHB in Denmark. *The suited area the potential caverns and storage capacity are calculated based on the same percentage as France (0,4%).

Stratigraphical Unit (Geological Division)	Structure	Total salt area (EHB corridors) [km^2]	Suited area* [km^2]	Potential caverns*	H2 storage potential* [TWh]
Upper Permian (Zechstein)	diapiric salt and layered salt	12 906	52	254	36

Regarding brine disposal the authors have no information about existing brine processing industry in Denmark. It is also not known whether brine discharge into the open sea is a realistic option with respect to Danish legislation. Nevertheless, for comparison with both previously evaluated countries it should be assumed that the same percentage of the salt area (1% for Germany, 0.4% for France) could be used for the construction of hydrogen storage caverns. The total salt area along the EHB accounts for 12 906 km², which is reduced to a presumably suited area of 129 km² or 52 km² with the scaling factors obtained for Germany or France. This results in a hydrogen energy storage potential of 90 TWh or 36 TWh, which is significantly more than the expected storage demand of 0.7 TWh (2030) or 5.3 TWh (2050). It remains an open question, if large numbers of new caverns can be developed in Denmark, when the local storage demand is already satisfied.

5.4. Benelux

As mentioned in [10-12] from the Benelux countries only the Netherlands possess for salt structures which give the possibility to build storage caverns. The salt structures as well as the corridor along the planned EHB [14] (20 km to both sides) are shown in Figure 5.7.

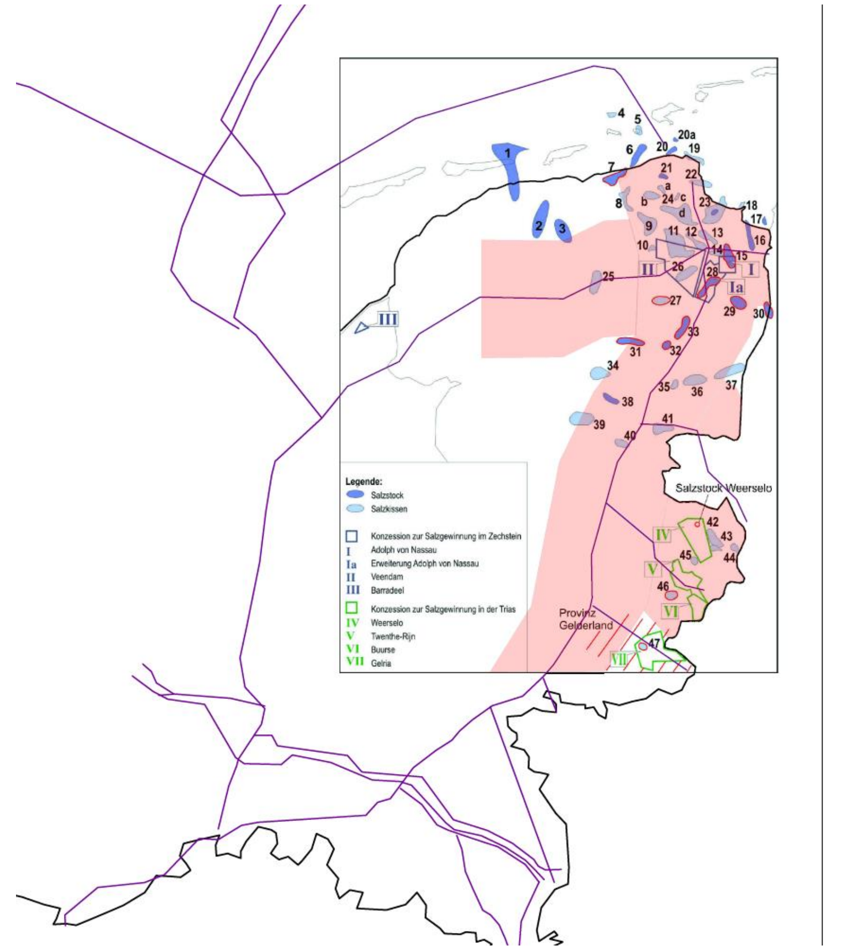


Figure 5.7: Salt structures in the Netherlands [10] in the vicinity of the EHB (2040) [14].

Using the same approach to evaluate salt structures based on individual properties like in Germany the Permian unit both as diapiric and pillow salt show a potential area of about 84 km² close to the planned EHB (2040). This could lead to a hydrogen storage potential of roughly 60 TWh in the Netherlands (Table 5.4) if no further restrictions are considered. Considering the expected storage demand of 6,3 TWh (2030) or 31,6 TWh (2050) [4] it is questionable, if the development of more than 400 new caverns is regarded as necessary in the Netherlands. The necessity to use the produced brine in industrial processes as well as infrastructural setup may limit this hydrogen storage potential further. However, it is known that a well-developed brine pipeline infrastructure is existing in the vicinity of the salt structures in the Netherlands.

TABLE 5.4: Potential of storage caverns and H2-energy content close to the EHB in the Netherlands.

Stratigraphical Unit (Geological Division)	**Structure**	**Total salt area (EHB corridors) [km^2]**	**Potential caverns**	**H2 storage potential [TWh]**
Permian (Zechstein/Rotlieg)	diapiric salt and layered salt	84	413	59

5.5. United Kingdom

The salt structures in the UK are based on [10]. Together with the corridors along the planned EHB (20 km to both sides), they are shown in Figure 5.8.

Using the same approach to evaluate salt structures based on individual properties like in Germany the Triassic unit dominates in this case over the Permian unit in extension. The Permian unit finds an end in the northeast of the UK. Both units show a potential area of about 75 km² close to the planned EHB (2040). This could lead to a hydrogen storage potential of 52 TWh in the UK if no further restrictions are considered.

Infrastructural setup and brine disposal issues may reduce this calculated hydrogen storage potential but cannot be evaluated in this work.

TABLE 5.5: Potential of storage caverns and H2-energy content close to the EHB in the United Kingdom.

Stratigraphical Unit (Geological Division)	**Structure**	**Total salt area (EHB corridors) [km^2]**	**Potential caverns**	**H2 storage potential [TWh]**
Permian	diapiric salt and layered salt	10	49	7
Triassic	Pillow salt	65	317	45
	Total	**75**	**366**	**52**

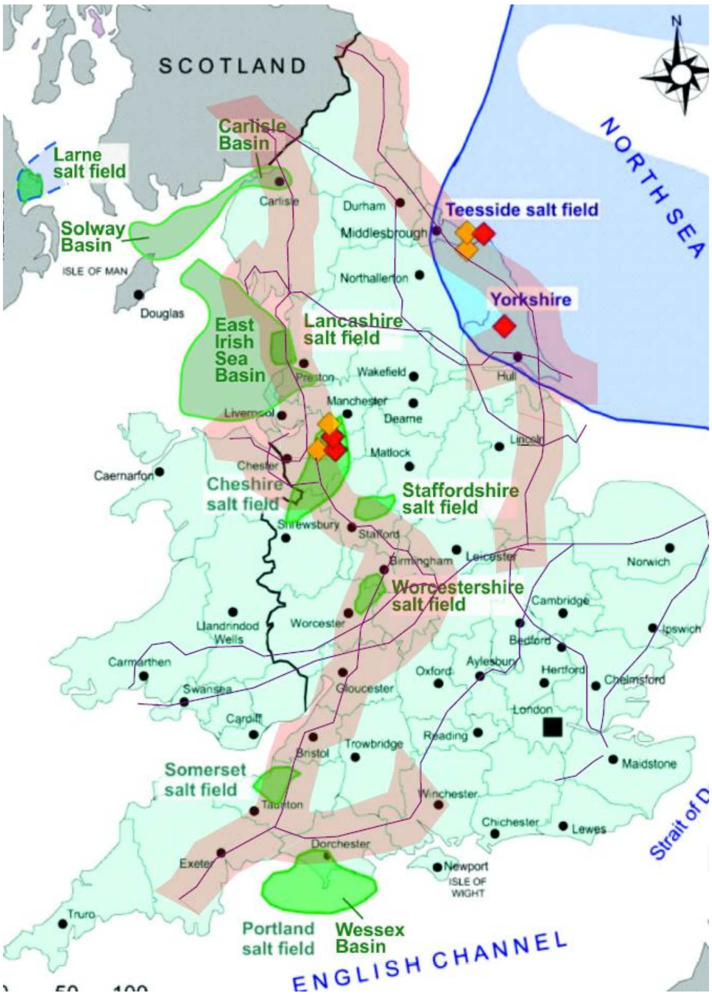


Figure 5.8: Salt structures in the United Kingdom [10] in the vicinity of the EHB (2040) [14].

6. CONCLUSIONS

The potential to develop new salt cavern storages for hydrogen has been evaluated for five European countries based on literature data on the spatial distribution of salt formations and own information about the suitability of these salt structures for cavern development. The resulting areas for cavern development have then been restricted to the vicinity of the planned European Hydrogen Backbone and where applicable to the surrounding of brine disposal options (brine processing industry or open sea). In Table 6.1 the resulting potentials are compared with reference data on the expected storage demand and the potential arising from the conversion of natural gas storage caverns.

Especially for Denmark, France and Germany, there are large areas with existing salt structures, which have not been included in the evaluation, because they are located beyond the defined maximum distances to the EHB or brine disposal options. In reality these are no hard limits, but the economic feasibility of developing a storage in these areas would suffer from higher costs for pipeline connections, which is a critical factor for many storage development projects.

From the figures in Table 6.1 it is obvious that the conversion of natural gas storage caverns alone will not provide sufficient storage capacity to meet the demand for 2050. For 2030 converted natural gas caverns could provide a large part of the projected demand, but it is highly questionable if they are available. Thus, the development of new caverns for hydrogen storage will be crucial to provide sufficient storage capacity for the future hydrogen market.

For most of the investigated countries the identified potential for new caverns is in the same order of magnitude or even larger than the projected storage demand in 2050. The potential of the five countries would even be large enough to serve the demand of whole Europe (in fact already the potential identified for Germany would be sufficient). On the other hand, the identified potential is in a similar order of magnitude as the projected demand, which means that a large part of the identified areas actually has to be used for hydrogen storage caverns and thousands of new caverns have to be constructed.

TABLE 6.1: Summary of hydrogen storage demand figures and geological potential. The storage demand and potential for conversion of natural gas storages are taken from [4], the potential for new caverns are the figures derived in this work for development of standard caverns in a 20 km corridor along the EHB and in a maximum distance of 50 km from the closest point for brine disposal. *The figures for total Europe taken from [4] include all European countries with reported demand and gas storages, while the potential for new caverns only sums up the five countries investigated in the present work.

Country	**Hydrogen storage demand 2030 [TWh]**	**Hydrogen storage demand 2050 [TWh]**	**Hydrogen storage potential (converted natural gas caverns) [TWh]**	**Hydrogen storage potential (new developed) [TWh]**
Denmark	0.7	5.3	1.3	36
France	8.2	43.1	2.5	23
Germany	15.9	111.4	39.5	501
Netherlands	6.3	31.6	0.9	59
United Kingdom	6.9	57.9	3.7	52
Europe (total)*	**72.2**	**466.4**	**50**	**671**

However, it should be kept in mind that the evaluations in this work are of theoretical nature and cannot replace an individual feasibility study for each site under consideration for storage development. Even though the authors have chosen a conservative approach regarding the usability of the identified salt areas for cavern development, there is always the possibility that site-specific aspects (e.g. salt quality, conflicts regarding land usage etc.) are not sufficiently reflected in the applied reduction factors. These aspects would typically lead to a reduction of the storage potential rather than an increase.

It should be reminded that the usage of salt caverns for gas storage in Europe started in the 1970's and it took several decades until the currently existing storage capacities (244 TWh of natural gas in the EU and UK corresponding to presumably 50 TWh of hydrogen storage capacity) have been developed. Now, the storage industry is challenged to develop 9 times this capacity within 25 years. Considering that the timeline for the development of new cavern storages is in the order of 10 years [16] and that only 9.1 TWh are already announced in Europe for 2030 [16], we must expect to run into a significant shortage of hydrogen storage capacities in the next decade. In addition to the geological storage potential, the timeline for investment decisions and for authority approvals, the availability of certified material and personnel capacities for storage planning and construction as well as the capacities for brine disposal all over Europe can become limiting to the provision of hydrogen storage capacities. This situation will surely have an effect on market development and on prices for hydrogen and storage capacities.

In the present work no significant differences could be identified between the dimensioning of storage caverns or sites for natural gas or hydrogen. It seems generally favorable to choose large cavern volumes and depths subject to geological and technical restrictions.

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8. ANNEX A – ELECTRONIC FILLING IDENTIFER

Document Name and version	<Overview of best suited cavern configurations for specific hydrogen storage demand figures (Deliverable D2.9, final version)>
Description	< This document summarizes the evaluation of industrial scale cavern configurations and identifies the available hydrogen storage potential in 5 European countries with respect to geological conditions and distances to the planned hydrogen pipeline system as well as brine disposal options.>
Location	<Project sharepoint\Deliverables>
Filing date	<23/08/2024>

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