Natural Gas Storage in Salt Caverns - Present Status, Developments and Future Trends in Europe

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1 Abstract

The increasing depletion of natural gas fields in central Europe and the accompanying need to transported gas over extremely long distances, as well as the liberalisation of the gas trading business, is currently feeding the market for additional gas storages – mostly in salt caverns.

This paper looks first at the status quo: the geographic spread of the stock of gas cavern storages in Europe, the current technical standards and the geological requirements for the installation of additional storages. This will be followed by a discussion of the latest trends and developments, and the associated geotechnical and technological challenges.

Unlike in the past when cavern storages were primarily constructed in thick, homogeneous salt deposits at favourable depths between around 900-1700 m, the European expansion in demand for storage capacities means that less favourable salt deposits also have to be utilised. This primarily involves thinner and inhomogeneous salt sequences at depths which are either very shallow or very deep.

New challenges also result from the increasing demand for merchant storages, which are characterised by frequent turnover and high deliverability. The associated modus operandi of such caverns increases the mechanical and thermal stress on the host salt rock. This has demanded the development of advanced dimensioning concepts.

2 Introduction

25% of Europe’s primary energy consumption is covered by natural gas. Natural gas consumption in Europe (EU 25, Norway, Switzerland, Romania, Bulgaria and Turkey) reached over 530 billion m$^3$ in 2005 of which around 300 billion m$^3$ or 55% was produced in Europe (mainly UK, Norway and the Netherlands). Around 230 billion m$^3$ of natural gas, or 45% of the total consumption, was produced in non-European countries (primarily Asian regions of Russia, Algeria; www.terragas.at). Europe mainly imports its natural gas through pipelines, only 12% of the imports are supplied as LNG from sources in North Africa, Nigeria and the Middle East.

As global energy demand rises, natural gas is increasingly replacing crude oil as one of the main energy sources because natural gas is the most environment-friendly fossil fuel with the lowest CO$_2$ emissions and there are much higher reserves of natural gas than crude oil (GERLING et al. 2005). The strong increase in natural gas consumption in Europe overall, against the background of diminishing domestic gas production, increases Europe’s dependency on natural gas imports from remote third countries. This in turn
increases the importance of natural gas storage to ensure supply security (e.g. BARBKNECHT 2006).

The natural gas storage volume in 20 countries in Europe in 2006 was almost 80 billion m$^3$ ($V_{st}$ working gas). This was stored in porous and cavern storages, and accounts for approx. 15 % of the annual demand. The largest shares of the total stored volume in Europe are found in Germany (19 billion m$^3$ $V_{st}$), Italy (17 billion m$^3$ $V_{st}$) and France (11 billion m$^3$ $V_{st}$) (IGU 2006, SEDLACEK 2006). This disguises, however, the huge variation in the proportion of storage capacity to total consumption in each European country (Fig. 1): Latvia’s storages for instance account for more than 100 % of annual natural gas consumption, whilst the storage volume to annual demand ratio of only 4 % in the UK is the lowest proportion in Europe.

![Figure 1: Specific storage capacity of some European countries (modified from web.wintershall.com).](image)

Gas storages are primarily built to balance out the strong fluctuation in seasonal demand, and for peak shaving. Storages are important for establishing continuous supply and production from remote gas fields and to optimise the efficiency of the pipelines. Gas storages are also vital for strategic gas purchasing, securing gas supplies, and bridging technical or political shortfalls in deliveries.

The dynamic growth in storage capacities currently taking place in Europe reflects a number of different factors:

- The decline in gas production in the UK means that the country is changing from a gas exporter to a net gas importer, a situation which requires storages (currently only accounting for approx. 4 % of annual consumption)
- Liberalisation of gas trading has initiated a demand for trading storages
The increasing importance of gas supplies from remote regions requires additional storages for seasonal balancing and to compensate for any supply shortfalls.

Storages are needed for the gas grids being built in countries such as Spain and Portugal with increasing number of gas-fired power plants.

Cavern storages are gaining in significance in this context because they can be more flexibly operated than porous storages, and the specific costs and risks are much lower compared to aquifer storages.

The subsequent discussion focuses on the geological and geotechnical aspects of the construction of future natural gas cavern storages.

3 Summary of gas cavern projects in Europe

Cavern storages account for approx. 11.5 % of European storage capacity, i.e. around 9 billion m³ (Vₘₚ). This low proportion is attributable to the much higher overall capacities and the lower investment costs for constructing pore storages in depleted oil and gas fields (SPRECKELS & CROTOGINO 2002). The following first discusses the status of European gas cavern storage projects in more detail and then looks at the geological and geotechnical potential for additional projects in Europe.

3.1 Status quo and planned projects

Gas storage caverns currently exist in six European countries. They are located at 28 different sites (or 34 cavern facilities) of which 17 alone (or 23) are in Germany, four in the UK and three in France. Denmark, Poland and Portugal each have one salt cavern gas storage (Fig. 2). The working gas volume in the 229 European gas storage caverns is around 9 billion m³ (Vₘₚ) of which 6.8 billion m³ (Vₘₚ) or 75 % lies in Germany (158 caverns) (Tab. 1). This concentration of cavern storages in North Germany highlights the favourable geological conditions for the construction of cavern storages in North Germany and Germany's favourable position overall relative to the existing North European natural gas suppliers in Norway, the Netherlands, the UK and Russia.

The expansion of 14 gas cavern storages (64 caverns) is planned for the near future. This involves an increase in the available working gas volume of approx. 3.5 billion m³ or around 39 % of the current volume. 12 storages with an additional 3.2 billion m³ (approx. 90 %) are to be expanded in Germany alone, whilst the other three are in France, Poland and the UK (Fig. 3, Tab. 1). The large number of expansion projects in Germany highlights the country's favourable position with respect to Russia as the main gas supplier and enhances Germany's position as a transit country.
In addition to the expansion projects, 15 new gas cavern storages are planned and under construction with a working gas volume of approx. 7.1 billion m$^3$. Six of these projects with a planned working gas volume of approx. 4.5 billion m$^3$ (approx. 64 %) are planned in the UK alone (Fig. 3, Tab. 1). The large proportion of planned new caverns in the UK highlights the urgent need in that country for the construction of extra storage capacities. The UK only became a net natural gas importer in recent years and is the third largest consumer of natural gas worldwide. Three new storages are planned in Germany. The Netherlands and France both have one storage under construction. Bulgaria plans to construct its first gas cavern storage.
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| TOTAL | 229 | 9060 | 64 | 3525 | 31 | 107 | 7115 |

*estimated

Table 1: Present status, extensions and new projects of natural gas cavern storages in Europe - Data compiled from Sedlacek (2006), IGU (2006) and current press releases.
3.2 Geological and geotechnical potential for gas cavern projects

Favourable conditions for the formation of rock salt deposits existed in Europe during the Permian, several periods during the Mesozoic, and in the Tertiary. Figure 4 shows a map with the distribution of underground salt deposits and all of the existing cavern fields in Europe (GILLHAUS et al., 2006; HORVATH & GILLHAUS, submitted).

The notable concentration of gas cavern storages in North Germany is primarily attributable to the geology as well as Germany’s central position in Europe for gas...
transport/import and gas storage. All of Germany’s 23 gas cavern localities are associated with the thick Palaeozoic salt laid down in the Permian.

Figure 4: Underground salt deposits and cavern fields in Europe (modified from GILLHAUS et al., 2006; HORVATH & GILLHAUS, submitted).

Structures with Rotliegendes salt (Lower Permian) only exist in the extreme north of Germany. These deposits consist of inhomogeneous breccias with NaCl concentrations averaging only approx. 60 – 80 vol.-%. The high proportion of insolubles (claystone) considerably diminishes the net volume of the caverns at the only Rotliegendes storage locality located near Kiel.
The high quality **Zechstein** salt deposits (Upper Permian) in the Central European basin systems usually have very favourable properties for gas cavern construction because of their large thickness and their high proportion of halite (> 90 vol.-%). The following are found at suitable depths in the German Zechstein salt sequence

- The widespread occurrence of bedded salt with thicknesses exceeding several 100 m
- More than 200 salt domes with salt thicknesses of more than 1000 m in part

In the salt domes in particular, it is important to find solution-minable salt with the lowest possible number of interbeds of easily soluble potash salts within the ideal depth interval of 900 to 1700 m. Poorly soluble interbeds (anhydrite, claystone) occur very rarely in the salt domes which are therefore highly suitable for the construction of cavern storages.

Other salt domes containing high quality Zechstein salt sequences at suitable depths are found in the north-eastern Netherlands (14 salt domes), north-western Denmark (16 salt domes) and Central Poland (10 salt domes). The Zechstein bedded salts in these countries tend to lie at excessive depths too deep for the construction of gas cavern storages. The geological/geotechnical potential for gas cavern projects in these countries therefore considerably exceeds demand.

The UK’s position at the edge of the Zechstein Basin means that the sequences of pure Zechstein salts are much thinner than on the Continent. The depths at the localities used so far for the construction of storages also tend to be deeper than 1700 m (Zechstein 2) or shallower than 500 m (Zechstein 3). The ratio of technical/financial costs to the capacity of the storages is therefore much more unfavourable than most of the other gas cavern fields constructed in Zechstein salt.

Other gas cavern storages are successfully operated in Mesozoic salt (UK, Portugal) and Tertiary salt (France)

**Bedded salt of Keuper** age (Lower Triassic) is used for gas storage at two localities in the western UK. They lie at depths of less than 700 m and have a high proportion of insolubles (claystone). These non-salt layers can be up to 10 m thick and therefore hinder the solution mining process and restrict the volume of the caverns. It is also much more complicated to confirm the integrity of caverns built in such unfavourable salt formations. Nevertheless, the technical and economic feasibility has already been proven for several sites and the construction and planning of other gas storage projects in these formations are thus under way.

Keuper salts of similar quality are used in the rest of Europe for brine production at various localities (Fig. 4). The Keuper salts are found as bedded salt, salt breccias or salt
domes and have generally been considered in the past to be unsuitable for the construction of gas storages. However, the growing demand for storage capacities at some localities in Spain, France and Switzerland could stimulate the exploration of these salt sequences.

In Portugal, there are salt domes with salt laid down at the Triassic-Jurassic boundary and which lie at suitable depths for the construction of gas cavern storages. The first and so far only gas cavern storage on the Iberian peninsula was constructed at Carriço in Portugal. Although the salt in the salt dome used for the cavern storage consists of an inhomogeneous breccia containing large non-salt blocks, there is probably additional potential for the construction of other storages along the west coast of Portugal.

Thick tectonised bedded salt of Tertiary age is used for the construction of gas storages in France. They contain high concentrations of insolubles compared to the North German salt structures, but have adequate potential for the future thanks to the homogenous nature of the salt and the suitable depths.

The Tertiary salt formations in Europe are very localised. Nevertheless, all of the deposits are used, at least for salt production. Most of the deposits are very strongly tectonised bedded salt sequences (salt breccias). There are also large salt domes of Tertiary age in Rumania. In Rumania and possibly also in southern Italy, the Tertiary salt is known to be thick enough and at suitable depths for the construction of gas cavern storages.

### 4 What’s new?

#### 4.1 Past and future storage objectives and the associated demands

Although cavern storages tend to be more suitable for the shaving of consumption peaks, they are often also used for seasonal balancing. Figure 5 shows the wellhead pressure of such a cavern over a period of several years. The liberalisation of the gas market has opened up a new application for short-term gas trading (arbitrage). The technical consequences of this are more frequent turnovers, higher deliverability, and especially injectability and higher rates which significantly raise the stress in the salt surrounding the cavern.

#### 4.2 Use of less favourable salt formations

The increasing demand for gas storage capacities and the construction of flexible merchant storages in particular has generated a cavern construction boom. This means that salt formations previously considered less suitable also have to be taken into consideration in addition to the prime sites mainly used in the past.
Figure 5: Well head pressure of a gas cavern for seasonal storage including peak shaving.

Most of the existing gas cavern storages in Europe were constructed in the past in relatively simple, largely homogenous salt structures including thick bedded salt sequences and salt pillows (e.g. Epe, Bernburg, Etrez), as well as salt domes (e.g. Nüttermoor, Ll. Torup) which developed from thick primary bedded salt sequences and salt pillows as a result of halotectonics. The stability and integrity of a cavern constructed in homogenous salt structures of this kind is primarily determined by the properties of the surrounding salt (Fig. 6).

Figure 6: Influence of salt and non-salt on the integrity of caverns in homogenous and inhomogeneous salt formations.

The expansion or construction of new storages is usually realised in favourable salt formations of this type wherever possible. North Germany benefits from the frequent win-win situation where favourable locations from a gas business point of view are often
associated with geologically favourable salt formations: EWE AG for instance plans to construct a new gas cavern storage in the only suitable salt structure (Möckow) right next to the landfall of the Nord Stream Pipeline (planned for commissioning in 2010, cf. Fig. 3). Most countries in western, southern and south-eastern Europe have less favourable geological conditions available for the construction of gas storage caverns even though almost every salt deposit in Europe contains caverns for brine production or the storage of other media (Fig. 4). However, the salt formations here are usually thinner than in northern central Europe and also often at unfavourable depths for gas storage. The salt sections suitable for cavern development are also often inhomogeneous. Thin salt sequences at unfavourable depths are associated with small cavern volumes and/or small differences between maximum and minimum permissible pressures – which all increase the cost per cubic metre of stored working gas.

In addition, the integrity of caverns constructed in inhomogeneous salt structures no longer solely relies on the quality of the surrounding salt: they also have to rely on the favourable interaction between different geological formations. Non-salt formations in such cases can be in direct contact with the medium in the cavern or in the immediate vicinity (Fig. 6). This involves e.g.:

- Salt formations with a large proportion of insolubles (> approx. 15 %)
- Competent insoluble beds (e.g. dolomite, anhydrite, clay) above and/or below the cavern
- Competent insoluble beds which cut through the cavern zone
- Faults in non-salt layers near the cavern

The exploration and feasibility-testing of unfavourable salt formations is often associated with much higher costs for in situ tests, laboratory analysis and computer modelling.

The UK is an example of a country where a number of such inhomogeneous salt structures requiring high exploration and planning costs have to be used – it is also the country with the highest demand for additional capacity (see above). All of the localities are affected by thin salt formations at depths which are normally considered either quite shallow (Cheshire in the west) or quite deep (East Yorkshire, Devonshire). These problems are exacerbated by the inhomogeneity of the salt formations, particularly in the west.
5 Consequences

5.1 Rock-mechanical design

Modern merchant storages place higher and quite different demands on the rock-mechanical design of the salt caverns involved. This is because of the more frequent turnovers, the higher withdrawal rates, and particularly, the higher injection rates.

Unlike storages constructed in the past mainly for seasonable balancing plus some peak shaving - which were therefore only affected by one turnover per year - future merchant storages have to cope with up to ten turnovers per annum and the associated much higher injection and withdrawal rates. These demanding specifications for the storages – although probably not always required in practise – or associated with high pressure change rates $\frac{\Delta p}{\Delta t}$, which are much higher than the previously demanded maximum figure of $\frac{\Delta p}{\Delta t} = 10$ to 20 bar/d.

The thermo-mechanical stress on the rock is another aspect: the previous much lower withdrawal rates, and especially the much lower injection rates, led to a comparatively low gas temperature rise or drop because the surrounding salt rock is a good thermal conductor and can therefore reduce peak temperatures. During the much more rapid changes predicted in merchant storages, there is much less time available to dissipate the heat generated. This will lead to the high temperature gradients along the walls of the cavern (Fig. 7). This could lead to cavern wall spalling which is only acceptable if the effects are very limited. The overall effect decreases with increasing cavern depth due to the increasing tangential stress component.

Figure 7: Temperature gradient in the cavern wall dependent on the gas rate.
Detailed laboratory investigations are currently being carried out by the Institute for Geomechanics and Waste Disposal Technologies at the Technical University Clausthal, Germany, to look in detail at the behaviour of salt under cyclic loading.

5.2 Thermodynamic design (gas hydrates, deliverability, turnover frequency)

The most crucial parameter for the performance of a modern gas storage is less the overall working gas volume than the deliverability, the proportion that can be withdrawn from the storage at the planned rate without any interruptions. Very high rates are generally required of modern merchant storage caverns, and should be maintained in some cases over long periods of time (Fig. 8). This causes a rapid temperature drop in the gas as it leaves the cavern and thus early undercutting of the gas hydrate temperature and the critical temperature for the annulus protection fluid at the cavern head in case of gas production strings. This means that the length of time for withdrawal is not so much restricted by the mass of gas that is present but the gas temperature (Fig. 9). The addition of gas hydrate inhibitors can only partially compensate for this negative effect.

![Figure 8: Deliverability vs time.](image)

On the other hand, the hydrate formation risk is reduced by storage operations with frequent cycles because the dry gas injected into the cavern for a relatively short period can only absorb minor amounts of water vapour from the cavern sump and therefore not hold enough water forhydrate formation to take place.
This problem can be solved by conducting numerical simulations of the thermodynamic conditions based on large amounts of empirical data on comparable operations.

### 5.3 Drilling and completion

The present maximum diameter of the gas production string (9-5/8") currently limits the withdrawal and injection rates as well as the withdrawal duration. This size is necessitated by the maximum 9-5/8" diameter of the subsurface safety valve (SSSV) stipulated by the authorities in Europe.

Production strings with larger diameters of up to 18 5/8" are standard in the USA where no SSSVs are stipulated.

Use is therefore made in Germany of monobore completions to achieve the maximum possible cross-section using the stipulated 9-5/8" diameter and thus achieve the highest possible withdrawal and injection rates under these conditions. The first gas cavern project to be realised in the Netherlands will also be the first to increase the flow cross-section of the production and injection strings by installing a twin borehole (Fig. 10).

### 5.4 Modus operandi

Opposite to gas caverns liquid product caverns are operated under constant pressure: this is done by displacing the brine into a surface brine shuttle pond during the injection of the product from where the brine is reinjected into the cavern to displace the liquid during
withdrawal (Fig. 11). The disadvantage is the installation of large surface brine shuttle ponds and the necessary piping to shuttle the two media in and out of the cavern.

Natural gas caverns are operated by compressing the injected gas and decompressing the withdrawn gas (sliding pressure operations). This has the advantage of no need for a surface brine pond, no need for a brine string; the disadvantages are that the gas cannot be completely withdrawn and so the cushion gas remains in the cavern under minimum pressure and that the caverns are exposed to fluctuating pressures between minimum and maximum pressure. Particularly in modern merchant storages, the sliding pressure method gives rise to very frequent and fast pressure changes resulting in high stress to the surrounding salt rock.

Therefore under certain unfavourable geotechnical conditions (thin salt sequence, very shallow or deep salt formations, re-use of large existing brine cavern e.g.), the constant pressure method may provide a more favourable option for realising gas storage caverns. An example of this is the hydrogen cavern facility operated by SABIC Europe in Teesside, UK, which has been successfully operated for many years.

![Figure 10: Twin borehole solution for the Zuidwending natural gas storage (modified from www.agbzw.nl/home).](image-url)
6 Cavern storages for LNG receiving terminals

The supply of natural gas from increasingly remote regions is leading to a partial shift of gas transport from pipelines to LNG chains. One of the features of LNG tanker transport is the need to unload the tanker within only a few hours at the receiving terminal.

![Diagram of constant pressure storage brine shuttle operations.](image)

**Figure 11:** Constant pressure storage brine shuttle operations.

A new concept – the *Bishop process* – uses cryo pumps to increase the LNG pressure, the warmth of seawater to evaporate the LNG immediately upon unloading and to inject it at cavern pressure into salt caverns in gaseous form. The expected advantages are the lower costs and much higher safety. However, the extremely fast unloading times of a tanker which holds enough gas to fill the whole working gas volume of a typical gas cavern places completely new demands on gas cavern design. The first concept study for the application of the Bishop process to the conditions existing in Europe was published in CROTOGINO et al. (2006).
7 References


