“Assessment of the potential, the actors and relevant business cases for large scale and seasonal storage of renewable electricity by hydrogen underground storage in Europe”

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R E P O R T

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1 Introduction

Geological storages which act as buffers to balance out temporal differences between the production and consumption of gases – primarily natural gas – have been successfully operated for many decades around the world. They are a key element of the present natural gas infrastructure worldwide.

In comparison with above ground storages they are protected from by a cover rock of many hundred meters of thickness. Underground storages provide large storage pressures and thus high energy density. In conjunction with the large volumes achievable in geological storages they also enable centralised facilities. Their advantages are high safety standards, a much lower foot print and much lower specific investment costs.

The different storage technologies described in this report are strongly dependent on the different geological formations utilised for storage purposes. Because the specifications for future hydrogen storages do not differ in any significant way from today’s natural gas storages, a great deal of experience can be put to valuable use for the evaluation of hydrogen storage options.

This report investigates a range of storage options looking at their suitability for the storage of hydrogen. All known storage options were looked at here which enable the storage of large volumes of hydrogen in underground geological formations. The technology, the existing experience, and the suitable geological formations are described for each of the storage options. This provides the basis for determining the technical feasibility of hydrogen storage with these storage options.

This Deliverable 3.1 within Work Package 3 “*Assessment of geological options for hydrogen underground storage”* provides an overview of the existing storage options, the way they function, their performance specifications, and their potential and risks, to provide a basis for the selection of the storage option which appears most suitable for the storage of large amounts of hydrogen. A subsequent selection is undertaken on the basis of a catalogue of criteria derived and described in Deliverable 3.2. The selection itself is undertaken on the basis of benchmarking and is documented in Deliverable 3.3. The aim here is to elaborate a shortlist with three key storage options which are considered to have the greatest long-term promise for the large scale industrial storage of hydrogen in geological formations.

Please note, however, that the storage options which are not considered should not be understood as being fundamentally unsuitable: The use of such options may be dependent on additional research being carried out, or cannot be used as a supra-regional storage option but rather as a niche option. In-detailed description of the key storage options followed by a final ranking is performed in Deliverable 3.4.

The following first compiles the selected storage options followed by a description of the presentation structure used to describe each of the options. Each of the storage options is then described in detail in dedicated chapters according to this structure.

1.1 List of Storage Options

In Europe and other regions around the world, there are dense grids of natural gas pipelines including integrated gas storages. In rank order of their storage volumes, these gas storages in geological underground formations are almost exclusively located in depleted gas fields, aquifer formations or artificially constructed salt caverns, see Figure 1-1.

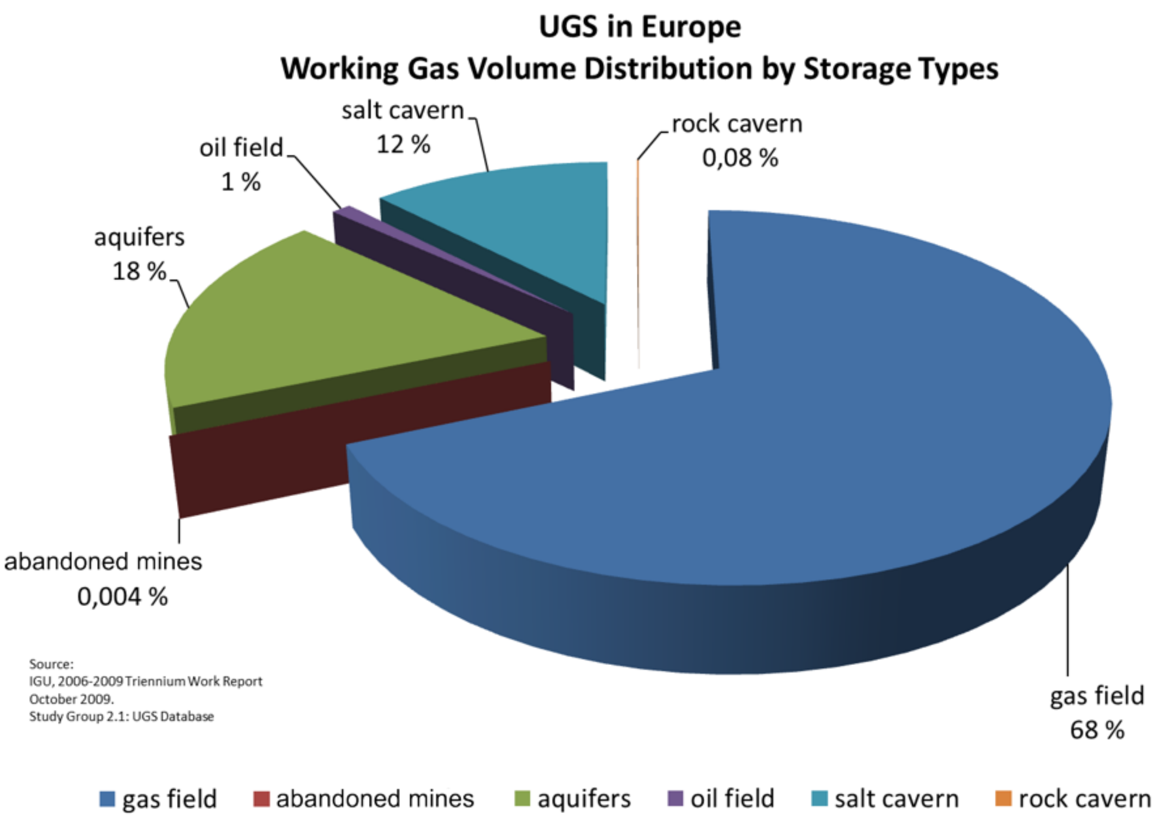

Figure 1-1: Distribution of natural storage options (basis: working gas volume) [30]

In very rare cases, storages have also been constructed in depleted oil fields, abandoned mines or rock caverns. Rock caverns are classified as those underground workings which are deliberately excavated using mining techniques for the specific purpose of creating gas storages. Abandoned mines on the other hand were constructed for the purpose of excavating a natural resource (production mines).

An additional storage option involves pipe storages, but these are not considered to be geological storages in the strict sense of the definition. They are buried at shallow depths (a few metres). They are therefore largely independent of the local geological situation and can be used almost anywhere, even in areas where the geology is unsuitable for the other options. Furthermore it appears to be a suitable interim option for the transition period when only small storage capacities are initially required before a mature hydrogen market has been fully established.

To enable a specific assessment of all of the different types in the subsequent ranking of the storage options, they are subdivided as follows when looked at in Deliverable 3.2 and Deliverable 3.3.

- salt caverns
- aquifers
- depleted fields
    - depleted oil fields
    - depleted gas fields
- conventionally mined rock caverns
    - unlined rock caverns
    - lined rock caverns
- abandoned conventional mines
    - abandoned salt mines
    - abandoned limestone mines
    - abandoned coal mines
- pipe storage

1.2 Structure of storage option description

All of the above listed storage options will be briefly described separately in the subsequent six Sections by following the below stated structure.

Description of Technology

The section begins with an outline of the key elements of the storage system and the basic mode of storage operation. This is followed by either design considerations e.g. for salt and rock caverns where the storage design can be influenced, or selection criteria e.g. for abandoned mines and depleted fields where it may only be possible to select between given options. Corresponding the construction or conversion to create a gas storage facility will be described, as well as methods used to seal the storage, and the operating procedure.

Experience

In this section, practical experience with the selected storage option will be discussed. Most existing knowledge is based on gas storages for natural gas. However, experiences are also available from the storage of LPG (liquid propane and butane), carbon dioxide, compressed air (Compressed Air Energy Storage, CAES-Projects) and town gas (a.k.a. light gas or coal gas). Practical experience in the storage of pure hydrogen is so far only available from salt caverns.

Required Geological Formations, their Occurrence and Potential

All the discussed options have the same requirements: to create a long term stable storage that is gas tight. Nevertheless, each storage option needs appropriate geological formations to fulfil these requirements. The formations range from sedimentary formations like sandstone for reservoirs, rock salt for salt caverns, and strong competent rocks for rock caverns. The occurrence of these rock formations in different regions and qualities within Europe are described.

Feasibility

In this section, the feasibility for future use of the various storage options for high pressure hydrogen storage will be discussed. The topics which are discussed are health, safety and environment (HSE) considerations, the required R&D effort based on the present state of the art, the estimated investment costs, and the general likelihood for future hydrogen storage applications. Estimated storage costs are provided in tabular form in Appendix A.

Please note that these costs do not include electrolyser, compressor and further gas handling devices to keep the effort for the benchmarking in this work package reasonable.

Performance / Characteristics of the Storage Options

Based on designs for existing gas storages, the performance and other technical characteristics for selected storage facilities will be described and extrapolated for the hypothetical storage of hydrogen.

2 Salt caverns

Salt caverns are artificially created cavities built in salt deposits. They are suitable for the storage of liquid hydrocarbons and in particular for gases under high pressure. Large amounts of gas can safely be stored due to large geometrical volumes and high storage pressures. Depending on the cavern depth, pressures of 200 bar and above are common. Geometrical volumes reaching up to more than 1 million m³ can be constructed. The special properties of rock salt guarantee the long term stability and gas tightness of the cavities, when operated within suitable pressure ranges.

Compared to other underground excavations very low specific construction costs are achieved because creation and operation of the caverns is done from above ground through only one single well bore, which is equipped with special piping and equipment. No technical installations are required underground except for this well.

Hydrogen has already been successfully stored in salt caverns in UK and the US for long periods of time and therefore appears feasible within short term in Europe.

2.1 Description of Technology

Design considerations

Salt caverns are gas tight due to unique properties of the rock salt. Additionally, the salt pillars with large widths/thicknesses beneath, above and below the cavern respectively, which are required for the rock mechanical stability of the host rock, combine this gas tightness with thick layers of sealing salt.

Rock salt deposits can be structured in salt domes, salt diapirs and bedded salt. Depending on its occurrence the salt may be contaminated with insolubles, however, in general this will not impair its tightness.

Applicable storage pressures depend on the cavern depth, operational scheme and range roughly between 80 % and 30 % of the lithostatic rock pressure. At a common cavern top depth of 1,000 m, this corresponds to a maximum pressure of some 180 bar and a minimum pressure of about 65 bar, see chapter 2.5.

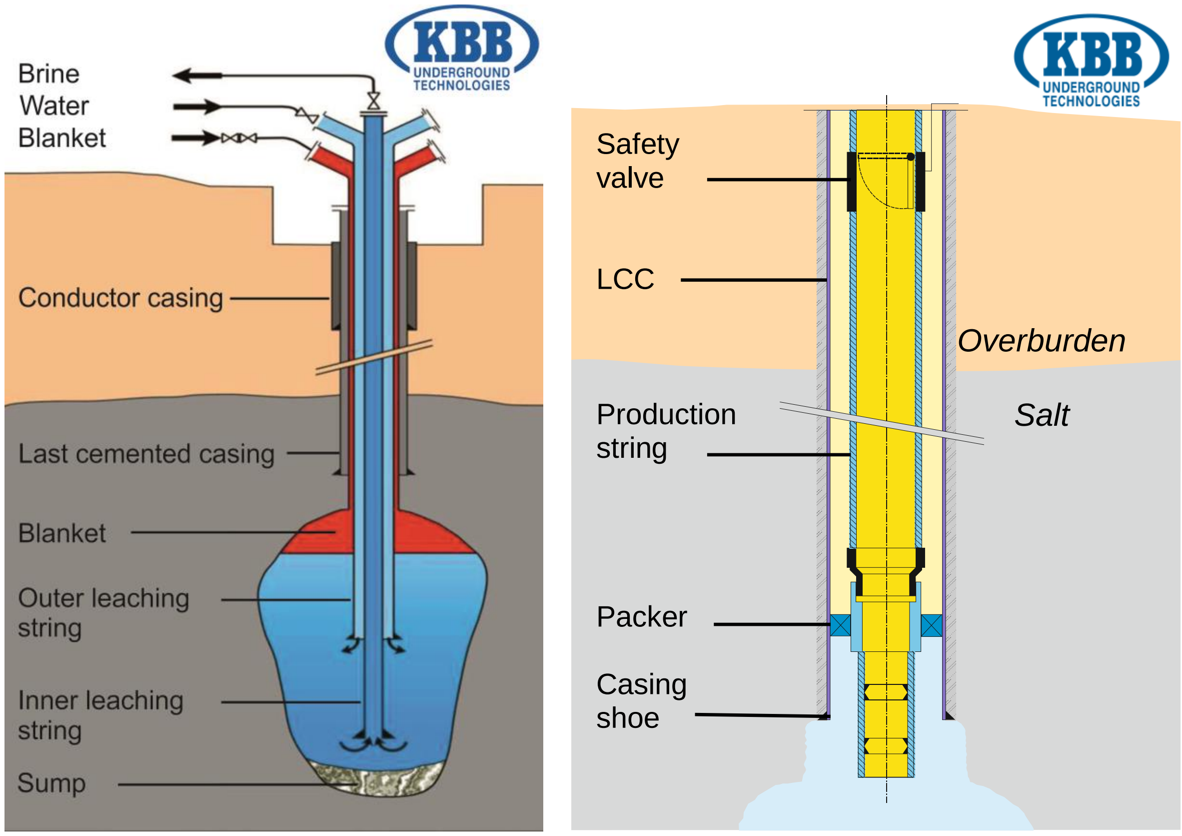

Figure 2-1: Salt cavern with installed leaching string and blanket during leaching (left) and gas completion (right)

Construction

At first, a well section is each drilled and prepared for the conductor casing and the surface casing. The void between casing and rock and in between the casings is cemented to the surface. These cemented casings provide safe conditions to drill the access to the salt formation which is envisaged for leaching the storage cavern. Then a final casing is installed and also cemented to surface. This piping reaches into the salt formation (last cemented casing, LCC) to isolate the salt deposit in the roof of the interval which is considered for the leaching process, Figure 2-1 (left). Two additional pipes (leaching strings) are then concentrically suspended in the well and fixed in the well head. The well section below the LCC is leached by injecting water through the inner one of these leaching tubings. Rock salt is then dissolved by water and the resulting brine is displaced from the cavern via the inner annulus. During leaching a blanket medium which has lower density than brine or water (commonly nitrogen or oil) is injected through the annulus between outer tubing and LCC. This prevents the salt in the upper part of the cavern from being accidently leached and helps to control the leaching process and thereby guides the cavern geometry development.

The cavern shape is controlled at regular intervals by sonar surveys. Depending on the measurement results, the leaching tubings depth, the flow direction and the blanket depth can be changed to optimise the leaching process and to keep the cavern within permitted dimensions.

The leaching process is stopped when a cavern reaches the planned size or is about to exceed permitted dimensions. Then, the leaching tubings are pulled out of the cavern and the mechanical integrity of the cavern bore hole is determined by a tightness test, which is commonly required for commissioning.

Prior to gas operations the gas production string and other elements of the so-called gas completion and the debrining string are installed, see Figure 2-1 (right). During the first fill of the cavern gas is injected through the annulus between the production and debrining string, and in parallel, brine is produced out of the cavern through the debrining string. The debrining string has to be pulled out of the cavern under gas pressure when the brine is completely displaced (snubbing), and prior to normal gas injection and withdrawal operations.

The construction period (drilling to commissioning) takes up to five years, depending on cavern volume and leaching rate. Brine produced during leaching and first fill of the cavern has to be disposed of in an environmentally sound manner, for instance by supplying it to a chemical engineering process or discharging it to the sea.

Operating procedure

Gas caverns are normally operated by compression and decompression between a minimum and a maximum pressure (sliding pressure method). Thus the gas inventory can be divided into working gas, which can be withdrawn from the cavern during normal operation, and cushion which must remain in the cavern to ensure its stability. Roughly estimated, about one third of the gas inventory is required as cushion gas, depending on the geology, depth, etc. When injecting and withdrawing the gas, the operational pressure of the storage varies between the aforementioned pressure limits. Besides the maximum and minimum cavern pressure, the salt cavern operations are mainly restricted by the maximum pressure change rate per unit time to ensure stability, and also by the maximum flow velocities inside the well. Furthermore, so called re-healing times at higher storage pressures are required subsequent to times of very low pressures.

In special cases, the caverns can be operated at constant pressure by displacing the gas with brine from a surface brine pond and vice versa. This method may be selected as very shallow salt formations are available. By applying this technique, the required cushion gas can be almost reduced to zero; on the other hand, a large surface brine pond will be required.

During the cavern lifetime some brine will always remain at the bottom of the cavern (cavern sump) and water will evaporate in to the gas and increase its moisture. Gas drying is therefore required depending on the latter use of the hydrogen. No degeneration of natural gas or hydrogen has been reported so far, therefore the rock salt can be assumed as inert. Therefore gas cleaning is not required.

2.2 Experience

Natural gas has been successfully stored in salt caverns in Europe and USA since the 1970s. Liberalisation of gas markets in the EU generated a boom in gas storages in recent years. A reason for this is the high flexibility of salt caverns, which is of particular importance for gas trading markets and also for future hydrogen storages. The technology of gas storage in salt caverns has been improved continuously over the years to achieve higher safety standards and lower maintenance and operational costs. The experience from these more than 300 salt caverns in Europe utilised for natural gas storages can be largely applied to hydrogen storage projects.

In the 1970s, **town gas** with hydrogen fractions larger than 50 % was successfully stored in reservoir storages and salt caverns. However, no issues about biological or chemical degradation or other issues are reported in literature.

To date, pure hydrogen has been stored in three caverns in Teesside, UK, since 1972 and in two caverns near the US Gulf Coast in Texas since 1983, see Table 2-1 for details. Practical experience in U.K. and American hydrogen caverns has shown that **hydrogen** can also be safely stored in salt caverns for long periods of time. It is important to note however that the stipulations defined by the competent authorities in the US for the layout, equipment and safety verifications for gas caverns are not as strict as the stringent regulations stipulated in Europe. This is why the standard technology used in the USA cannot be taken over in Europe one-to-one.

Table 2-1: Existing hydrogen storage caverns in USA and UK

	Clemens (USA)	**Moss Bluff (USA)**	**Teesside (UK)**
Geology	Domal salt	Domal salt	Bedded salt
Operator	Conoco Phillips	Praxair	Sabic Petroleum
Stored fluid	Hydrogen	Hydrogen	Hydrogen
Commissioned	1983	2007	~1972
Volume [m³]	580,000	566,000	3 x 70,000
Reference depth [m]	930	> 822	350
Pressure range [bar]	70 - 135	55 - 152	~ 45
Possible working gas capacity H_2 Mio [kg]	2.56	3.72	0.83

Additional information about the storages listed in Table 2-1 is provided in Appendix A.

Generally speaking, the design and operation both for natural gas and for hydrogen are very similar. The major difference is related to material selection for the utilised equipment in case of hydrogen and safety measures at surface.

2.3 Geological Formations, their Occurrence and Potential

The mechanical behaviour of rock salt differs from most other rocks because of its remarkable visco-plastic properties in the applied pressure/temperature regime. This special deformation behaviour has two important consequences:

- Rock salt is technically gas-tight when affected by compressive stress. In other words, the tightness and integrity is solely guaranteed by the host rock itself. Therefore no additional sealing is necessary. Any fractures that may develop will close due to the rheological behaviour or rock salt.
- By visco-plastic deformation rock salt redistributes any stress peaks built up in response to the construction and operation of the caverns. It is because of this property that it is possible in the first place to construct and operate caverns with diameters of up to 100 m and more, with heights of several hundred metres, without artificial stabilisation measures.

Another important property is the high solubility of salt in water which enables the caverns to be constructed by leaching from the surface.

The rock salt deposits are divided into two types: stratiform salt deposits (bedded salt) and salt structures.

- Stratiform salt deposits display the original bedding of the rock, and the geometry of the rock salt zones are (sub-) horizontal, and cover very large areas (up to several thousand km²). The vertical extent of the salt deposits can be up to several hundred metres. Most European bedded salt deposits (Triassic and Tertiary age) lie at depths of up to 1,000 m. The salt deposits of Permian age (e.g. in Germany) lie at depths of more than 2,000 m.
- Tectonic movement of rocks can lead to the secondary accumulation of salt in salt structures. This increases the height of the salt deposits and gives rise to the formation of salt domes (salt diapirs). Salt diapirs can have heights of several kilometres, and can therefore be used to construct very high caverns. The genesis of salt diapirs also gives rise to complicated folding of the original bedding. Rock salt zones within salt domes can be tightly interfolded with non-salt horizons, which therefore complicate the planning and dimensioning of the salt caverns in such structures. In general, the rock salt zones suitable for cavern construction are concentrated in the centres of salt pillows and diapirs.

Before a cavern well is drilled, it is first necessary to carry out geological investigations (exploration drilling, seismic) to ensure that a safe distance is maintained between the cavern and the boundaries of the rock salt zones. This investigation will also determine the geological structure, salt quality and thus furthermore the mechanical properties of the rock as well as the applicable pressure ranges. Information on the depth and the vertical and horizontal extent of the salt deposit are acquired by carrying out geophysical surveys from ground surface.

Rocks such as anhydrite and claystone which cannot be leached and rocks such as potash salts which dissolve much faster than rock salt during leaching can have a negative effect on cavern construction. Information on the internal structure of the salt deposit is therefore important for the leaching concept of a cavern storage. This information cannot be gained from surface geophysical surveys but only from wells.

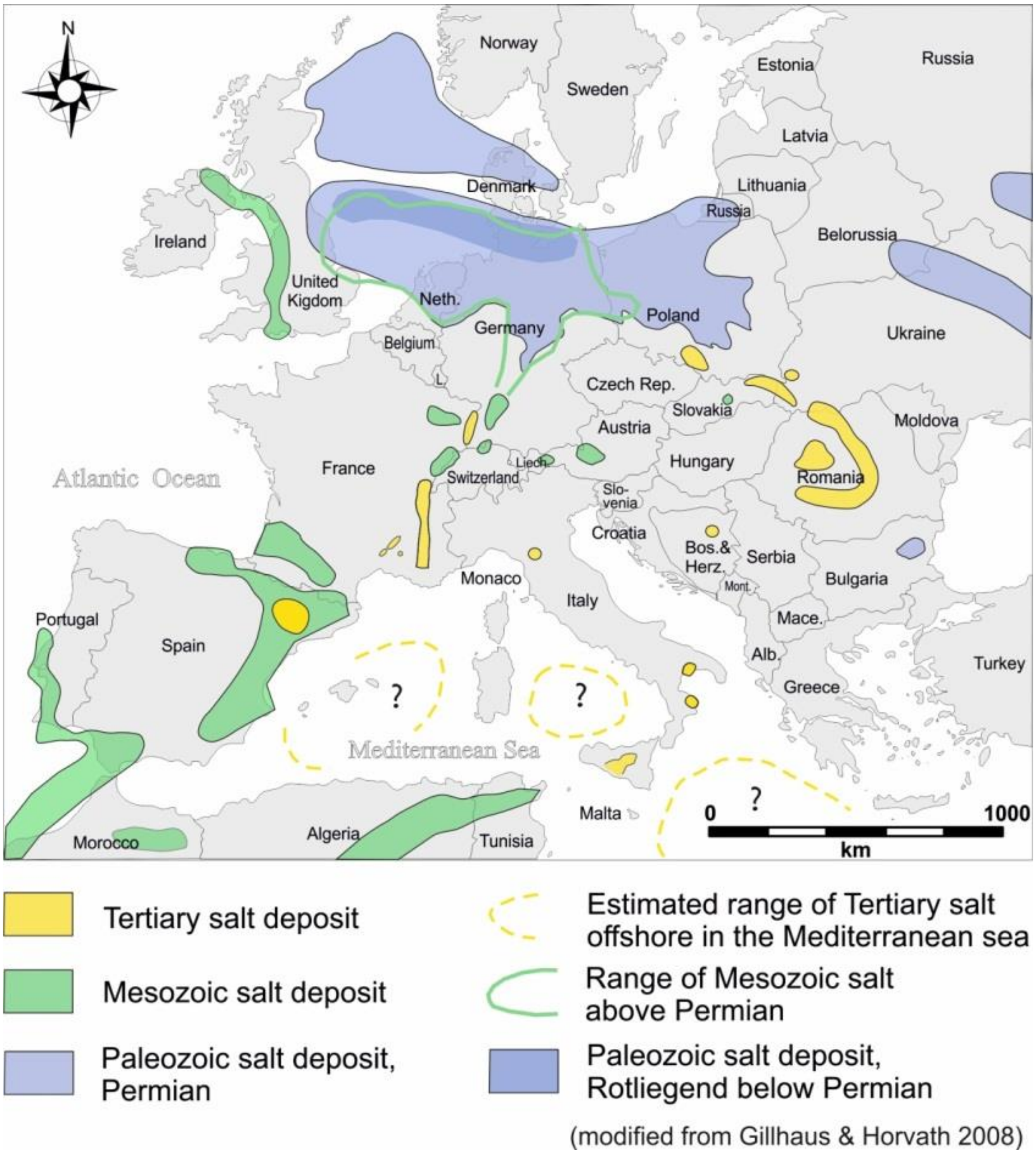

Figure 2-2: Salt deposits in Europe, [10]

2.4 Feasibility

As already discussed above, rock salt is for several reasons an ideal host rock for high pressure natural gas caverns:

- Tightness of rock salt for high pressure gases
- Ability to construct large, unlined caverns
- High storage pressures
- Low specific costs due to construction completely from surface
- Low footprint for surface installations

There is more than 40 years practical experience with several hundred natural gas caverns worldwide. In addition, positive experience has been acquired from the successful operation of hydrogen caverns in the UK and the US.

Even though the technology still needs to be adapted to satisfy the local safety regulations in Europe, salt caverns can be seen to be very suitable for the storage of high pressure hydrogen.

2.4.1 Health, Safety and Environment

The health safety and environmental issues involved in the operation of future hydrogen caverns are associated with the same hazards that can affect the operation of natural gas caverns. These include emissions during construction, brine disposal, the unhindered escape of the stored gas in case of a blow-out which is very unlikely because of fail-safe underground safety valves and the also very unlikely disaster of a cavern collapse and surface subsidence. Some of these are also the main subjects in environmental impact assessments for cavern construction projects.

In relation to the large number of natural gas caverns worldwide only few accidents happened. All of them could be attributed specifically to defective workmanship during planning, construction or operation. At worst these accidents led only to few injuries of persons, however, they never questioned the general ability of salt caverns to store gas. A worst case scenario would be the tearing off of the very robust well head with its multiple safety installations. However, a blow-out of a state-of-the-art cavern in Europe would still be prevented by an automatically closing subsurface safety valve (SSSV) which is located deeper than 50 m below the well head.

In case that the SSSV would also fail, stored gas would escape unhindered to the surface (blow-out) and would probably ignite to form a gas flare. The energy released by a blow-out of this kind is limited by the narrow cross section of the cavern well. Only a limited area surrounding the well would be affected. Safety distances of roughly 100 – 200 m are therefore required. Analysis has shown that a blow-out of a hydrogen cavern would emit slightly less thermal radiation and last much shorter than it would be the case with a natural gas cavern.

It is impossible for the gas stored in the cavern to ignite within the cavern itself because of the absence of oxygen which completely prevents the formation of a combustible mixture.

Rock salt creeps and begins to deform when affected by high formation pressures, but without losing any of its strength. Because of this creep the volume of a salt cavern declines over time. As a result, the surface above the cavern subsides evenly and very slowly as time passes (surface subsidence).

The long term stability of the cavern is ensured by many years of experience and by site-specific lab testing in combination with rock-mechanical models. These account for stress limits of the rock salt to derive the permissible cavern dimensions and minimum and maximum operation pressure.

A further issue to be addressed is the disposal of brine produced during the leaching process. A brine volume of roughly eight times the final cavern volume is produced during leaching and gas first fill. If the brine will not be used for instance in the chemical industry it is essential to be disposed in an environmentally safe manner. Commonly the brine is disposed via pipelines to the sea where it has very little impact to the salinity of bulk water. At some locations the brine is injected into appropriate geological formations.

A certain environmental impact occurs by emissions like noise, dust, light, etc. during construction of cavern pad, leaching and operation facilities as well as by workover and construction works and transportations. During the leaching process some rig assisted workover are required. During the operation no works are required at the cavern pad expect for few regular maintenance operations. Emissions will only occur at the surface installations.

2.4.2 Required R&D

Due to the long experience with natural gas storage in caverns, only a minor amount of well-defined extra research has to be performed to construct hydrogen storage caverns with European safety standards. Main considerations have to be to requirements for cement integrity and the specifications for the utilised equipment.

The cemented connection between the LCC and the rock salt in the cavern neck is identified to be the most sensitive point in the cavern. Therefore, the proper cement bond and the tightness related to hydrogen have to be confirmed, and if required, the cement mixture must be modified.

Although common steels are adequate to seal the hydrogen in the cavern, they might be damaged by hydrogen embrittlement. Therefore, suitable steels and also suitable flexible non-metallic materials like plastics and elastomer have to be approved for the required construction elements. Alternatively, more expensive materials like austenitic steels have to be applied which are proven to be suitable.

The cavern is sealed by thick rock salt walls which perfectly provide gas tightness. The gas tightness of the rock salt is determined specifically in laboratory test and thus do not need to be tested in-situ. To prove the gas tightness of the produced cavern wells mechanical integrity tests (MIT) are carried out in natural gas storages by injecting brine and the test gas nitrogen into the flooded cavern to reach the operational pressure, and by filling the well and the upper part of the cavern neck with the test gas. By metering the encased gas volume or by periodically refilling the test volume, a leakage rate can be derived and compared to the test criteria. Some development work might be required depending on the defined criteria and regulations for the modification of MITs for hydrogen caverns.

2.4.3 Costs

Investment costs of about € 28 Mio are estimated for the construction of a hydrogen storage cavern with about 500,000 m³ geometrical volume (€ 55 per m³ geometrical cavern volume) in a top depth of about 1,000 m³. These costs are conservatively estimated and can vary immense (20 – 50 Mio), depending on the available infrastructure and the knowledge about the geology at site. The estimate is based on materials of higher quality than used for standard natural gas caverns, and include exploration, drilling, leaching, first fill and all other engineering and management work (green field site). Additional costs for surface facilities, as e.g. gas compressor, electrolyser, gas dryer etc. are not included for this and hence also not for the following storage options. In general investment costs are reduced when well-known salt structures or pre-existing infrastructure can be used in case of expansion of a pre-existing cavern field (brown field). Increased experience in hydrogen storage will also help to reduce investment costs.

The investment to buy the amount of gas required to maintain the minimum required pressure (cushion gas) is also not included, due to the uncertainty of future hydrogen and energy prices respectively.

2.4.4 Risks

The risk that salt caverns in general might not be suitable to store hydrogen obviously is small, since some caverns already exist and only few R&D is required. As stated above it seems most likely that knowledge may be applied that is already available from other industries.

In planning and implementation of specific projects for the storage of hydrogen in salt caverns there are the same risks associated as with natural gas storage caverns.

The main risk of salt cavern storage projects is the geological uncertainty, which can be reduced by increasing the knowledge base on the specific salt deposit (exploration). For a given cavern location this risk includes e.g. the occurrence of non-halite interbeds, faults, distance to edge of salt structure, etc. All of these issues affect the rock mechanical layout of the cavern and may lead to a reduced cavern size, a reduced operational pressure range or even the requirement to abandon and plug the well.

Further risks are associated with the technical processes of drilling and cementing of the well, since failure in cementation will lead to a cavern leakage. During leaching the rock mechanical limitations must not be exceeded, otherwise the leaching strategy must be modified which will also lead to a lower cavern volume.

Brine disposal far from the sea shore is often an issue and may lead to higher costs by longer pipelines to suitable disposal spots. Brine disposal, subsidence and the aforementioned HSE issues often require an environmental impact assessment to be made, which may slow down or even hinder the permitting process.

2.5 Characteristic and Performance

The feasible geometrical volume of salt caverns depends mainly on the thickness of the salt formation. The volume may range typically from 150,000 to 800,000 m^3. Under optimal conditions in a huge salt dome volumes even above 1,000,000 m^3 have already been achieved. It is possible to create small sized salt caverns initially and re-leach them afterwards. However, flooding of the cavern and subsequent gas first fill is required in this case which increases the costs for these operations.

Operating pressures depend primarily on the cavern depth. The maximum pressures range from 100 to 270 bar, the minimum pressures from 35 to 90 bar respectively (orders of magnitude only).

For a common cavern volume of 500,000 m³ and a casing shoe depth of 1,000 m a pressure range of 180 to 60 bar is suitable, which results in a working gas capacity of 4.0 Mio kg hydrogen (47 Mio m³(st)) and a cushion gas of 2.2 Mio kg (26 Mio m³(st)).

Unlike depleted oil & gas fields or aquifers the interior of salt caverns does not consist of a porous structure. Natural gas caverns are therefore operated with high withdrawal and injection rates in relation to the working gas capacity. Furthermore, the high temperatures at common cavern depths provide a heat source during withdrawal compensating the gas cooling during withdrawal and helping to avoid too low temperatures. Depending on the cavern pressure, size and production tubing injection and withdrawal rates of more than 130,000 m³(st)/h or 105,000 kg/h are common for single natural gas storage salt caverns. Please note that commonly several caverns are operated in parallel to serve as one storage, with multiple times the stated rates.

Thermodynamic simulations show that the injection and withdrawal mass flow of hydrogen for such a cavern would roughly be one-tenth the natural gas rate (11,000 kg/h), if the same pressure change rate is applied as for natural gas caverns. This applies also for the injection. Nevertheless, injection is more often restrained by the possible throughput of the above ground facilities. Additionally to the maximum pressure rates the cavern operation might be restricted on the operation scheme or in limited operation times in the low pressure range.

As for natural gas hydrogen salt cavern storages provide supply for short, mid-term and also seasonal applications. Depending on the gas storage operation (seasonal or multi cycle) a number of up to ten gas turnovers per year is feasible. However, this number of turnovers does not represent multiple withdrawals down to minimum pressure, but the over one year integrated withdrawals and injections.

Gas drying is required for the gas withdrawn from a salt cavern, since some brine will always remain in the cavern and will evaporate in the gas. However, no purification is required for the vast majority of salt caverns.

3 Aquifers

Aquifers have been applied for natural gas storage in Europe since 1953 and their construction and operation is standard practice worldwide since many decades. Aquifers are porous and permeable rock formations containing fresh water or more commonly brine in the pore space. Typically such permeable rock formations are sandstones or carbonate rocks. In order to be suitable for gas storage, the aquifer needs to be overlain by a layer of impermeable cap rock. Such a cap rock could be tight shale, salt or an anhydrite layer.

Aquifers can commonly store large volumes of gas, but are rather inflexible to operate. Issues with biological and chemical reactions have to be investigated in order to apply these geological structures as hydrogen storage.

3.1 Description of Technology

In the exploration phase an aquifer with an overlying cap rock, needs to be identified. To prevent the gas from rising upwards and migrating out of the storage a three-dimensional shape which is capable of containing the gas is required.

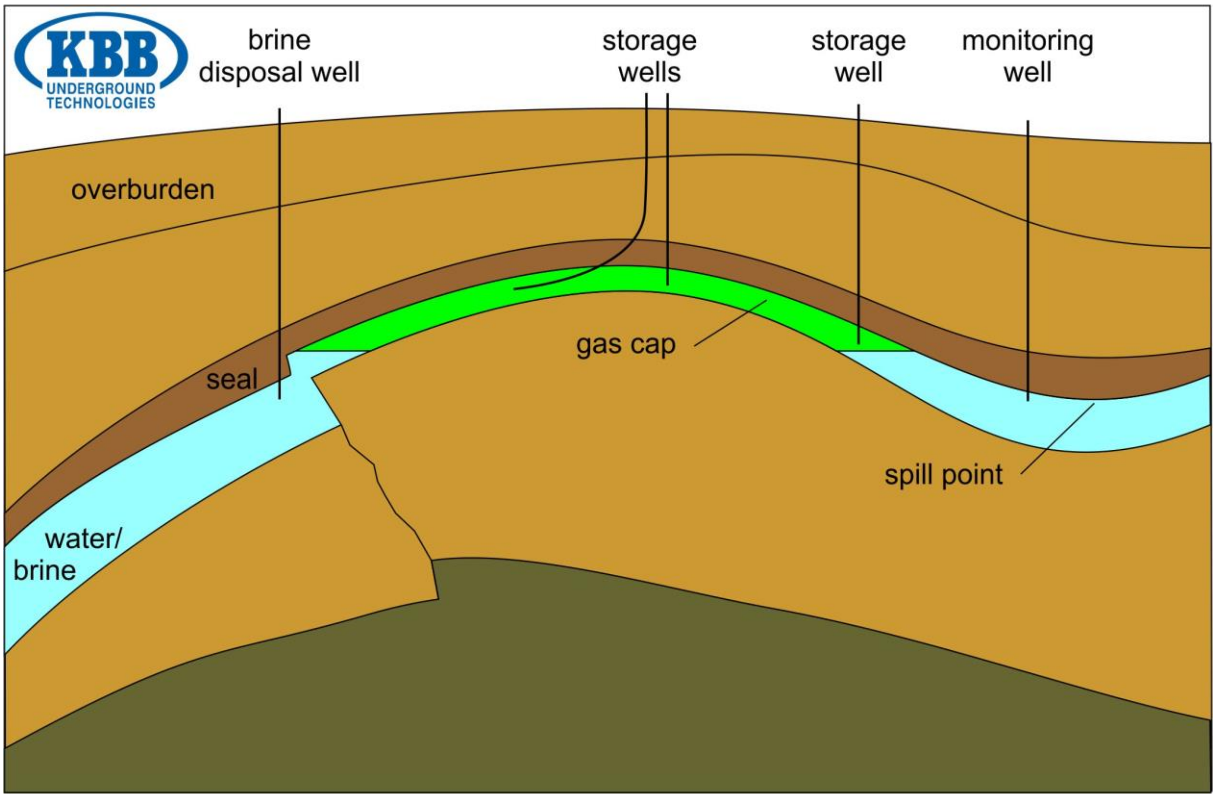

Figure 3-1: Sketch of gas storage in an aquifer.

This "container" is known as a "geological trap". Such a trap can be either a anticline as depicted in Figure 3-1 or another type (see also Figure 4-2 for further examples of traps). The size of the trap is defined by the spill point, which is the highest point where the structure is open to the connecting aquifer (or the lowest point at which the storage is closed for the product).

In order to develop a gas storage within a suitable rock layer, a number of wells are drilled through the overlaying rock burden and the sealing caprock layer into the aquifer. Similar to cavern storages the wells are drilled in several steps and after each step the annulus between the pipe and the surrounding rock is cemented. The integrity of the well is then tested by a pressure test. However, the pressure test is commonly performed with a liquid and therefore will only provide information about the tightness against liquids. Note that the final pressure test must be performed with a casing shoe that is located within the seal formation, before the connection to the storage formation is reached.

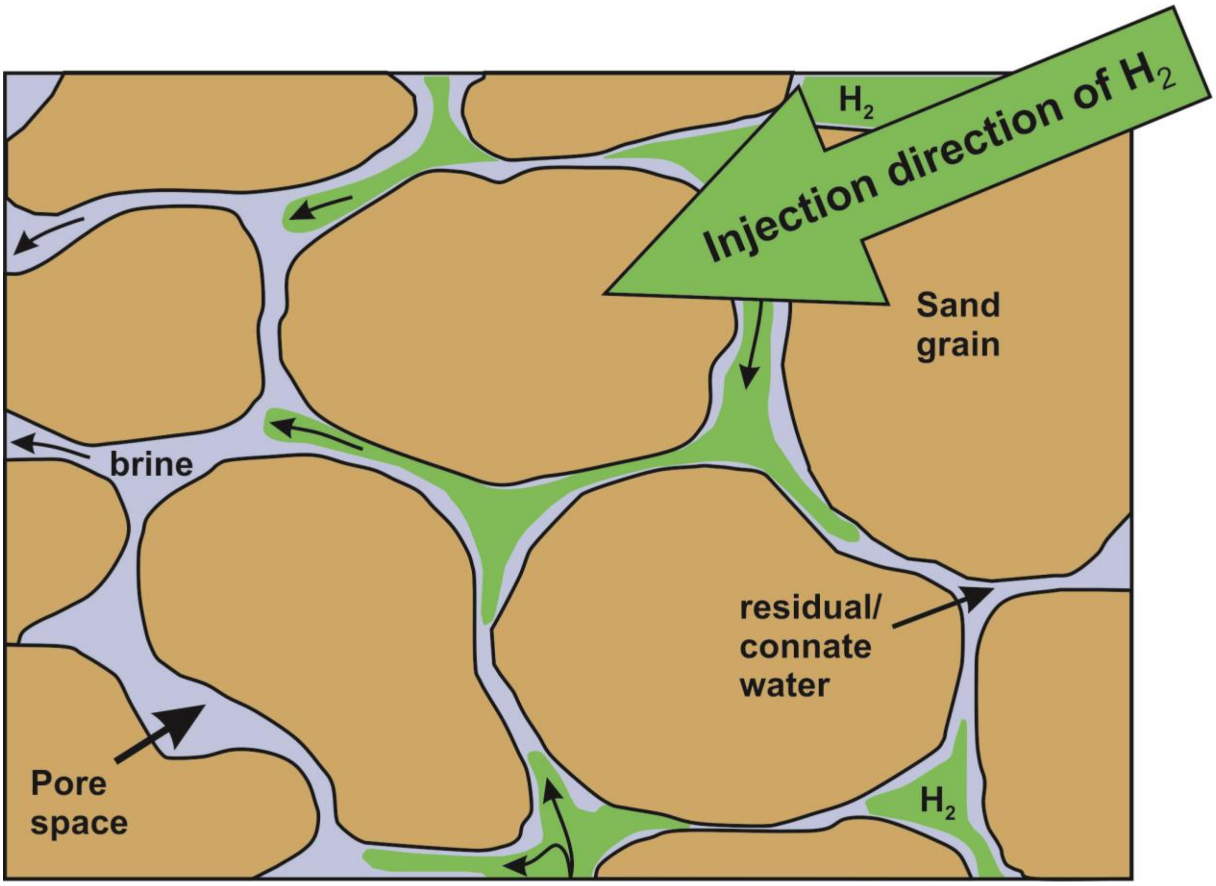

Figure 3-2: Gas migration in a water filled pore space.

The wells are used to inject the storage medium into the pore space. The pore space in the aquifer is initially filled with water or brine. Therefore, the capacity of the storage site is determined not only by the size of the container/trap and the porosity but also by their distribution and therefore the amount of residual water that will remain in the pore space after gas is injected, see Figure 3-2. After a suitable aquifer has been identified the development can take about four years.

Since the pore space in the aquifer is actually filled with water or brine, this liquid has to be pushed downward and to the side and subsequently the pressure will rise. This pressure increase depends on a number of parameters, such as the size of the aquifer (not only of the trap), whether it is an open or closed system and on the compressibility of rock and fluids and the permeability. The pressure increase has to be monitored carefully, as a maximum storage pressure should not be exceed (fracture pressure of the formation, threshold pressure) to avoid damaging the storage.

In a very large or open structure more gas can be injected, since the water can be pushed to the sides, obviously. In smaller or closed aquifers, the pressure will rise strongly due to compression and thus the quantity of gas injected before the fracture pressure limit is reached is smaller. The permeability of the rock will determine how fast the liquid can flow away or return and therefore also influences the pressure response of the aquifer. In an aquifer with high permeability the product (hydrogen) tends to spread over a larger area, leading to lower pressures near the injection wells. Consequently, the aquifer permeability and the maximum allowable pressure increase determine the maximum allowable injection rates for the gas.

During the withdrawal phase, the pressure difference between the well and the storage will push the gas back to the well. However, a certain amount of gas will remain in the aquifer and therefore cannot be recovered again. This physically unrecoverable gas will be lost.

Note that this is one of the major differences between aquifer and depleted gas field storages, since this portion of gas is already present in the pores of a depleted gas field. On the one hand the amount of unrecoverable gas is large and therefore requires a costly investment both in the case of natural gas and hydrogen storage, since the pore spaces of an aquifer need to be filled with gas initially. On the other hand in aquifers no gas mixing can occur between hydrogen and formation gases.

Fluid flow in the pore space of the rock matrix depends on the rock permeability, the viscosity of the fluids and if more than one fluid phase is present also on the relative permeability of these two fluids to each other. Depending on these parameters there can be significant differences in flow velocities. The flow velocities in aquifers consisting of a porous matrix are always much smaller than in an open cavity, like a cavern. Higher injection and withdrawal rates in aquifers can be achieved by using multiple injection/production wells or sometimes by using long horizontal wells, but both come at a cost. Nevertheless, low flow rates in aquifers are the reason that in natural gas storage this storage type is mainly used for seasonal storage, with only one annual storage cycle at steady injection and withdrawal rates.

Since the porosity of the reservoir and the behaviour of the liquid phase is the same for natural gas and hydrogen storage, differences between them can only arise from differences between natural gas and hydrogen itself. Since hydrogen has a lower viscosity and thereby a higher mobility one can assume similar volumetric withdrawal and injection rates compared to natural gas storage. Other differences are related to reactions between natural gas (mostly methane) or hydrogen and the host rock or microorganism.

3.2 Experience

Currently no data has been published of any storage of pure hydrogen in aquifers. However, there is plenty of experience with natural gas storage and also with town-gas in aquifers.

Natural gas storage in aquifers mainly is applied in regions where neither salt deposits, which are suitable for cavern construction, nor depleted gas fields are available. According to the GSE database [35] aquifer storage facilities for natural gas storage are operated at 25 different locations within Europe. These locations are spread over six European countries: Estonia, Belgium, Czech Republic, Denmark, France, Germany and Ukraine. The total working gas capacity of all locations is approximately 19,000 Mio m^3(st), which is in a similar order of magnitude as for natural gas storage in salt caverns in Europe [35].

Prior to natural gas, **town-gas** was stored in aquifers. Town-gas, a gas produced by coal gasification can be seen as good equivalent for hydrogen storage, since it consists of approximately 50-60% H_2. Further components are CO, CO_2, CH_4 and N_2.

Town gas was very common in Europe in the middle of the 19th century, before it was replaced by natural gas in the second half of the 20th century. For decades, town gas storage was done in salt caverns as well as in aquifers. Examples of sites where town gas previously was stored in aquifers are Engelbostel and Bad Lauchstädt in Germany, Lobodice in the Czech Republic and Beynes in France.

The experience with storage of town gas in Lobodice showed that after a few months of storage about half of the hydrogen was converted to methane. This was explained by biodegradation of hydrogen reacting with CO and CO_2 to methane [25]. This gas depletion can be tolerated in a town-gas storage but not in a storage for pure hydrogen.

Other issues with town gas storage in aquifers did result from non-hydrogen components in the gas mixture. However, these components will not occur in the injected hydrogen and the issues therefore are not relevant for pure hydrogen storages. Despite the experience with town gas storage only very little literature can be found about this topic.

A third source of experience with gas injection into an aquifer besides storage of natural gas and town-gas is the injection of carbon dioxide. In order to mitigate climate change due to CO_2 increase in the atmosphere, CO_2 can be captured from a combustion process and injected into a deep saline aquifer in a process called Carbon Capture and Storage (CCS). That is currently done in a number of demonstration projects for example in the oil and gas fields Sleipner and in Snøvit in Norway or in In-Salah in Algeria. However in CCS one is interested in a disposal, and not in retrieving the injected CO_2 afterwards again or even frequent turnover as is the case in natural gas or hydrogen storage. While CO_2 is seen and treated as a waste product, hydrogen is a valuable resource that should be recovered as completely as possible. Although the scope and the scale of CO_2 injection is very different from hydrogen storage, the data gathered when aquifers suitable for CO_2 injection where mapped all over Europe is a useful resource.

Exemplarily for all known aquifer storages some information about the rather small sized storage Hähnlein, near Darmstadt in Germany is concluded in the following [27]. At this site the gas is stored in a tertiary horizon, which lies in a depth of around 500 m and provides more than 30 % porosity. The storage was initially created in the 1960s for the storage of town gas and is now utilised as natural gas storage. Seismic survey and exploration drilling was originally performed prospecting natural gas. The aquifer structure was then further explored and operated by E.ON Gas Storage (former Ruhrgas AG). A total of 19 production wells and 5 observation wells have been drilled and allow for injection rates of 84,000 m³(st)/h and withdrawal rates of 106,000 m³(st)/h. The storage is operated at pressures ranging from 53 to 39 bar. The inventory of 170 Mio m³(st) can be split in 85 Mio m³(st) for working gas and cushion gas each.

A rather large storage, operated by DONG, is the Stenlille storage in Denmark, where natural gas is stored in a depth of 1,500 m in a sandstone formation with overlaying claystone. The storage is operated at a pressure range of 150 to 170 bar with an inventory of 1,060 Mio m³(st) and only 370 Mio m³(st) working gas. Thus about two thirds of the total gas in place is cushion gas. The structure is estimated to be capable to store up to 3,200 Mio m³(st) of natural gas in several separate zones [18]. 14 wells were drilled for production and 6 additional wells for monitoring of the storage. The wells were drilled from 3 different well sites.

Table 3-1: Natural gas aquifer storages

	Hähnlein (Germany)	**Stenlille (DK)**
Geology	Late Tertiary II	Sandstone
Operator	E.ON Gas Storage	DONG
Stored fluid	Natural Gas	Natural Gas
Commission	1960	1989
Volume [m³]	-	-
Reference depth [m]	~ 500	1,500
Pressure range [bar]	39 – 53	150 – 170
Possible working gas capacity H_2 Mio [kg]	6.27	19.04

Additional information about the storages listed in Table 3-1 is provided in Appendix A.

3.3 Geological Formations, their Occurrence and Potential

Aquifers occur in all sedimentary basins within Europe. Large sedimentary basins with aquifers occurring onshore can be found in Germany, Poland, France, Belgium, The Netherlands, Spain, Romania, and Denmark. As just mentioned, in order to estimate the potential for CCS, numerous studies on the distribution of deep, saline aquifers have been carried out and all potentially suitable aquifers in Europe were mapped [8]. The distribution of the larger aquifers is depicted in Figure 3-3. Most European countries, except for the Scandinavian Peninsula, have more or less extensive aquifers in sandstones or carbonates. However, only few of them are utilised as storage formation.

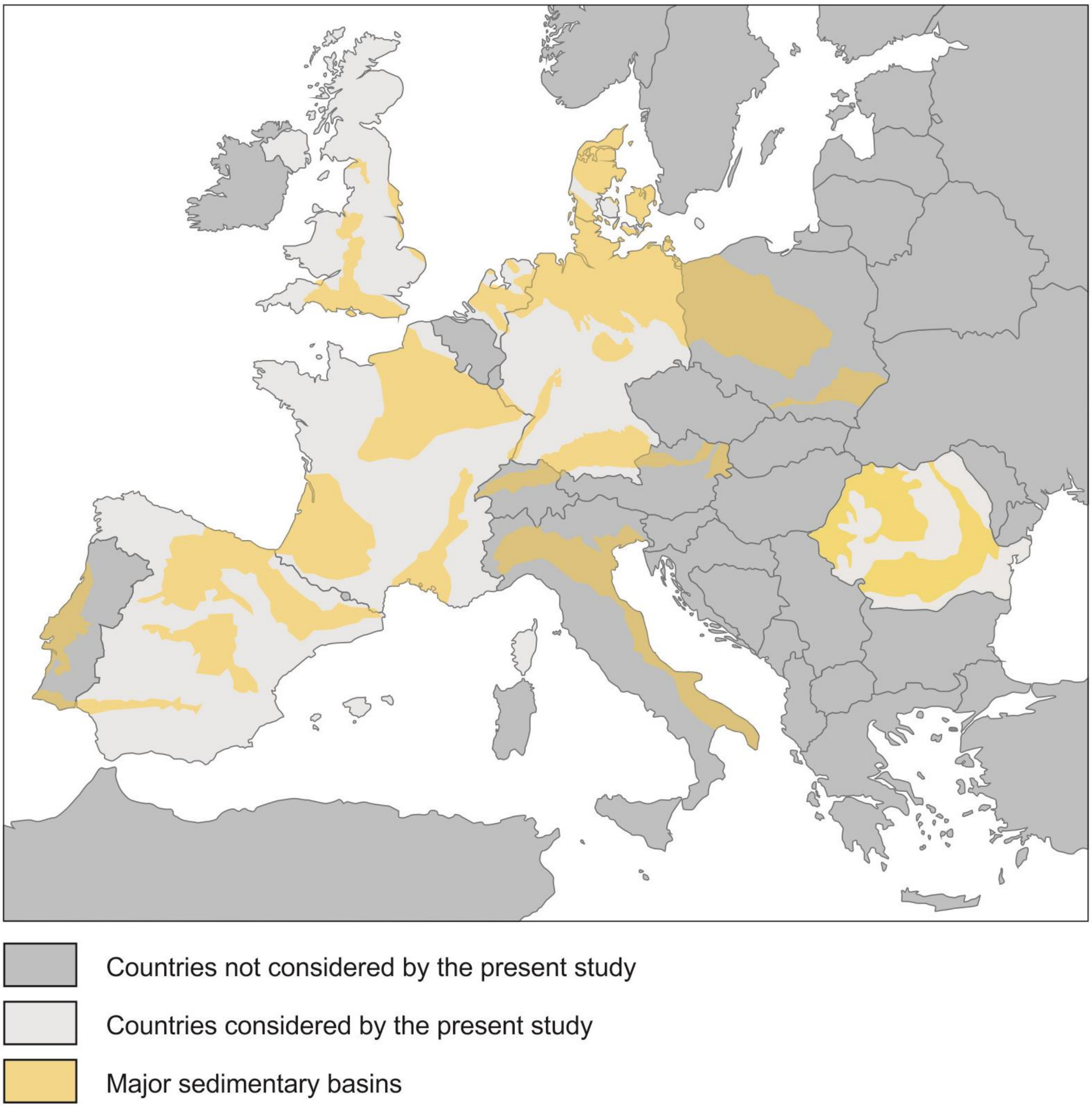

Figure 3-3: Distribution of aquifers in Europe, after [15].

3.4 Feasibility

A number of aquifers are operated safely and for many decades as natural gas storage. Therefore it is expected that HSE issues and risks will arise only from the more challenging properties of hydrogen interacting with the storage. Nevertheless, intense research is required to analyse the impact of chemical and biological reactions between hydrogen and the formation as well as to prove the tightness of the overburden against hydrogen.

3.4.1 Health, Safety and Environment

The health safety and environmental issues involved in the operation of future hydrogen aquifer storages include emissions during construction, the unhindered escape of the stored gas in case of a blow-out which is very unlikely because of fail-safe subsurface safety valves and the also very unlikely disaster of a leakage through faults or other leakage paths.

During exploration activities (seismic and exploration well drilling) and construction a certain environmental impact occurs by emissions like noise, dust, light, etc. during construction of the drill pads, gas handling facilities as well as by workover and construction works and transportations. During the operation no works are required at the well sites except for periodic maintenance.

Like for all underground storages the worst case scenario is an incident that leads to rip off of the very robust well head with its multiple safety installations. However, a blow-out would be prevented by an automatically closing subsurface safety valve (SSSV), installed some meters below the well head. In case the SSSV would also fail, stored gas would escape unhindered (blow-out) and would probably ignite to form a gas flare. The energy released versus time by a blow-out of this kind is smaller than for a cavern blow out because common well diameters for porous storages are smaller. Because of the commonly much larger inventory of aquifer storages the duration of the blow-out could last longer. It is impossible for the gas stored in the aquifer to ignite within the formation itself because of the absence of oxygen which completely prevents the formation of a combustible mixture.

Unlike than for depleted gas and oil fields the tightness of aquifer formations is initially unknown and has to be proven by geophysical testing. However, a limited risk remains that gas may leak, e.g. through unknown fractures or the spill point or other potential leak paths. These safety issues are commonly met by drilling of monitoring wells in the perimeter of the aquifer formation and the overlying cap rock. These are measures that are done additionally to wells which monitor the gas to liquid interface within the storage range of the formation.

During the conditioning of the aquifer for gas storage the load in the formation is increased in a way that the formation has not experienced, since aquifer formation have never been filled with hydrocarbons. This may lead to small movements in the overburden or even to an upheaval at the surface. Seismic monitoring around the storage during commissioning and the first years of operation can provide valuable information to optimise or limit the storage operations.

Conditioning and operation of the aquifer storage will influence deep and water bearing groundwater carriers since formation water will be pressed out of the storage. These processes need to be analysed or avoided in a way that fresh water contamination can be reliably excluded.

3.4.2 Required R&D

From the experience with natural gas storage, town-gas storage and CO_2 injection in aquifers it can be concluded that the list of potential risks for significant amounts of hydrogen to get trapped/lost or contaminated in an aquifer is long. Consequently a lot of R&D will be required to better understand the potential issues and find mitigation options for them. Most of the open questions are around the rock and fluids behaviour in the pore space with hydrogen present. The issues are:

- Tightness of potential cap rock sealing for hydrogen.
- Mineral reactions which could alter reservoir or cap rock.
- Bio-chemical reactions that will convert the hydrogen in e.g. methane.
- Chemical reactions between hydrogen and host rock minerals e.g. sulphur
- Unclear mobility ratio between hydrogen and brine and influence to fingering and sweep efficiency[1] .

A research program for a better understanding of the rock and fluid properties in the presence of hydrogen will require core flow experiments to measure permeabilites of water (brine) and hydrogen in aquifer rocks and capillary entry pressures of hydrogen

[1] Sweep efficiency describes that a certain domain of the formation cannot be used as storage since the formation water will not be displaced because of inhomogeneities.

in potential cap rocks like shale and anhydrite. Both are not routine laboratory measurements, hence guidelines and procedures for these measurements need to be developed. Most of the experiments would be very time consuming and require special facilities. The issue of biodegradation is most likely even more complex, since besides the aquifer brine chemistry and the mineralogy of the rock matrix, bacteria are involved.

Besides all open questions about the behaviour of hydrogen in the pore space and the containment of hydrogen in the aquifer, there are issues around well cementation and well completions. Like it was described for salt caverns, the cement bond needs to be approved for hydrogen storage and suitable steels and suitable flexible materials like plastics have to be approved for hydrogen.

3.4.3 Costs

Because of the barely predictable efforts for exploration and the required number of wells it can be assumed that the costs associated with the development of a hydrogen storage in an aquifer represents much larger uncertainties than the cost estimates for hydrogen storage in salt caverns or depleted hydrocarbon fields. In most cases the costs are expected to be higher than for the two other cases.

First, there will be significant costs for research, as briefly outlined in the previous section. If further research identifies aquifers as a viable storage option for hydrogen, the costs to select and develop an individual site will be high. The typical cost elements during the different phases of a storage project are:

- **Site selection process, pre-FID[2]:** Seismic survey, exploration wells, injection testing, laboratory test, modelling, permitting
- **Construction of infrastructure:** Drilling and completion of wells, installation of compressors and gas treatment installations
- **Hydrogen storage operations:**
    - Operation and maintenance OPEX for wells, compressors,
    - Amount of cushion gas and physically unrecoverable gas,
    - Treatment of back produced hydrogen (removal of contamination).
- **Site closure:** Decommissioning of wells and site

[2] Final Investment Decision

The site selection process will be very expensive, since multiple aquifers may need to be investigated until a site with suitable conditions and storage volume is found. The costs during site selection will come from seismic surveys and exploration wells. Once some potential storage sites are identified, storage characterisation will require appraisal wells for injectivity and laboratory tests. The costs for the exploration and appraisal phase are expected to be significantly higher than for storage sites in depleted hydrocarbon fields, since for aquifers usually no previous exploration data and no production history exists.

During the site construction phase injection/withdrawal wells need to be drilled and the surface infrastructure like compressors needs to be installed. While for storage sites in depleted fields, some existing infrastructure might be reused, like wells etc. this is not possible for aquifers.

The operational costs are mainly compressor related costs, which in turn are related to the flow rates and the injection pressures. Since aquifers are not pressure depleted, higher injection pressures might be required, which leads to higher compressor costs.

From natural gas storage it is known that aquifers have higher cushion gas requirements then salt caverns or depleted reservoirs. Additionally a very large amount of gas is required to initially set up the gas bubble in the aquifer. A large portion of this gas will therefore remain in the formation even after de-commissioning (unrecoverable gas). This, in-fact has a main impact on the overall project costs.

The issue of contamination of hydrogen was discussed before. Contamination will require gas treatment facilities, which tend to be very expensive, increasing the investment and the operational costs.

3.4.4 Risks

When storing hydrogen, the integrity of the storage container is essential. For safety reasons it is required to avoid hydrogen leaking to the surface. Since hydrogen is a valuable resource, there is also the economic risk of losing or not being able to recover all injected hydrogen. In an aquifer, there are a number of potential risks to lose hydrogen that need to be considered.

Most important the containment of the hydrogen in the aquifer needs to be ensured. The cap rock layer needs to be tight towards hydrogen and seal the storage efficiently. Leakage through the top seal and sideways migration out of the storage needs to be avoided. The spill point of the targeted structure in the aquifer and any potential aquifer flow must be determined for each individual site. Leakage of hydrogen along fractures and fault zones also needs to be excluded.

Furthermore the extension of the aquifer formation can only be evaluated by injection tests when an exploration well has been drilled. Too small extension of the formation represents a major risk for the storage project.

Biodegradation of hydrogen that was already mentioned as an experience with town-gas is a severe technical and economic risk. For town gas, the issue of methane generation was still acceptable, since the gas mix was used for combustion anyway. However, hydrogen used in fuel cells needs to have only a very low contamination of methane.

Another economical risk is that larger amounts of hydrogen might get trapped in the aquifer and cannot be recovered. A part of this trapping might simply be due to aquifer heterogeneity and unfavourable sweep efficiency, so that not all hydrogen will flow back to the injection/production well, but it might be bypassed and stay behind in the reservoir. Capillary trapping of residual gas, will also result in a permanent loss of hydrogen.

Besides the risks of losing hydrogen, there are operational risks, like the risk of well integrity, such as leakage through the well bore or the development of skin that might jeopardize injection or withdrawal rates. These operational risks are usually manageable, but mitigation might require expensive workovers.

3.5 Characteristic and Performance

The applicable sizes of aquifers vary widely and enable storages volumes much larger than for salt caverns. The hydrogen is injected in the upper section of the aquifer structure, thus the storage has certain scalability of the utilised storage volume. The applied vertical extends and volume of the formation can therefore be increased successively. Nevertheless a certain gas volume must always be reached to avoid aspiration of formation water in the well bore.

Working gas capacities of aquifers for natural gas storage per storage site are in the order of hundred to thousand million m^3(st) and could be in theory similar for hydrogen storage. However, the significant amount of unrecoverable gas which will remain in the formation is a vital problem when developing an aquifer storage.

Maximum gas withdrawal and injection rates per well depend on the rock permeability, the number of wells and the length of the well perforations as well as on volumetric extend and connectivity of the formation. Injection and withdrawal rates of about 85,000 kg/h (106,000 m^3(st)/h) of natural gas are common values. Typically only one gas turnover can be performed per year, since these rates are rather small related to the working gas volume. Because of the higher mobility of hydrogen compared to natural gas the same or higher volumetric flow during injection and withdrawal are assumed to be feasible. For the rates given above this would result in 14,000 kg/h.

High contents of water and impurities must be removed from the withdrawn gas, depending on the specific storage.

Summing up hydrogen storage in aquifers is similar to storage in depleted oil and gas fields. The differences are the higher exploration and site characterisation costs, much lower data availability, no issues of hydrogen mixing with natural gas but a large quantity of gas which cannot be recovered from the storage. The largest advantage of aquifers is, that they occur wide spread and could be an alternative where no salt caverns or depleted hydrocarbons fields are available.

4 Depleted Fields

Depleted oil and gas fields were filled with hydrocarbons in the past and a certain amount of these hydrocarbons have been produced (withdrawn). In contrast aquifer structures are geological traps which were not filled with hydrocarbons but with formation water. Since many years these two types of geological structures are used successfully as underground storages for natural gas.

The advantages of depleted fields are that these trap structures are well known from the time when the reservoir had been explored and tested and later when hydrocarbons were produced. Normally the gas fields are not completely depleted and the remaining gas can be utilised as cushion gas. Furthermore subsurface and surface installations already exist and may be used for later purposes. Hence, a conversion into underground gas storages may be possible with only limited exploration effort and investment as long as the above mentioned conditions are given. But this does not imply that all depleted fields are suitable for underground storage, especially not for hydrogen.

4.1 Description of Technology

Conventional subsurface reservoirs hold hydrocarbons like oil or gas in geological traps. These geological traps consist normally of reservoir, seal and aquifer, see Figure 4-1.

The main element is the reservoir or the hydrocarbon accumulation, which is the container for the hydrocarbons, where the hydrocarbons are found in porous and permeable sediments or rocks. The hydrocarbons are found in the spaces between the individual sand grains of porous and more or less homogeneous sandstones or in fractures as well as pores of carbonate rocks. All types of rocks are deposited in a whole variety of environments. In theses environments the miscellaneous lithologies, and here especially the reservoir rocks are deposited in different geological processes. In typical reservoirs the hydrocarbons in the accumulation migrate from the source rock, underneath the reservoir, along geological pathways into the final reservoir.

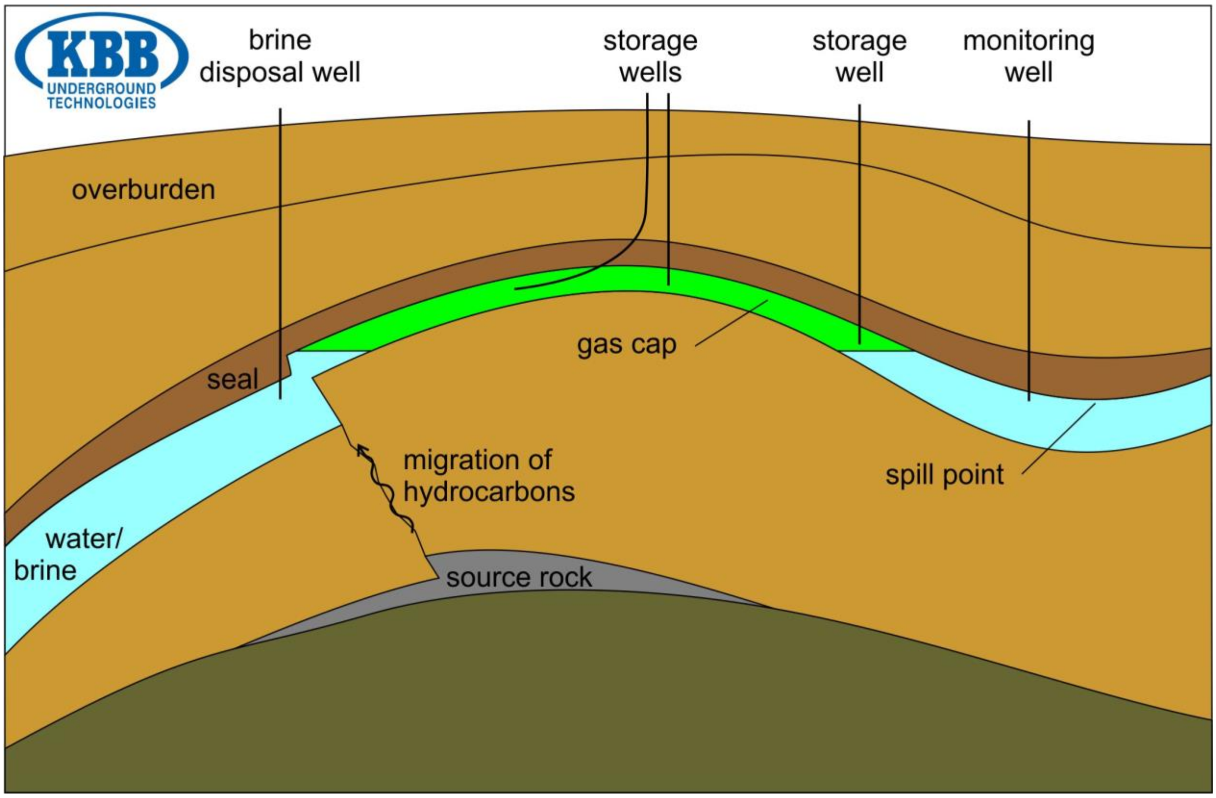

Figure 4-1: Schematic diagram showing a typical setup of a hydrocarbon reservoir

The second element of the hydrocarbon trap is the seal which covers the whole hydrocarbon reservoir. The reservoir seals are impermeable, tight rocks that hold back the hydrocarbons in the reservoir. The top seals are often thick and tight shale horizons, tight, non-fractured carbonates or even tight salt layers.

The third part of the hydrocarbon trap is the aquifer underneath the reservoir. The saline formation waters provide in many cases the pressure support for the reservoir. The overall reservoir pressure is the result of the pressure of the compressible hydrocarbons as well as the aquifer pressure and is smaller than the capillary entry pressures of the sealing rocks. This provides the full seal integrity; otherwise the hydrocarbons would penetrate the seal and would leak into the layers above the reservoir.

Conversion

The simplest way for the construction of underground gas storages is the conversion of suitable depleted gas fields. However, not all depleted fields are suitable for conversion to underground storages. Suitable fields need to fulfil certain prerequisites and need to provide certain subsurface properties to enable the successful storage and production of natural gas.

These prerequisites and properties are:

- a proven reservoir structure which can hold the hydrocarbons,
- a suitable depth which can be translated into an pressure range,
- sufficient, connected porosities to provide the gas capacities and
- sufficient permeability for good injection and production rates of the wells.

Because of the exploration and production history of the depleted reservoir a good knowledge of the subsurface conditions exists which supports the transformation into an underground gas storage. The available data and the understanding of the reservoir structure and behaviour demonstrate that the structure is large and capable enough to hold the gas in its porous and permeable horizons. Additionally the cover rock needs to separate the reservoir from shallower structures to prevent that gas can escape. Preferably depleted gas fields do not have a water drive, which helps to improve the gas recovery and results in less water production. Less water drive supports also a more efficient injection. In addition the surface installations including trunk- and pipelines are often still available for the storage operations and may at least help monitoring the storage. Commonly several storage wells are drilled during the conversion, since the former production wells were not optimised for storage operations. The newly drilled wells are tested with storage pressure tests, as described for the aquifer storages. However, the pressure test is commonly performed with a liquid and therefore will only provide information about the tightness against liquids. In Europe more than 120 depleted fields were converted in the past as natural gas storage facilities [35].

The majority of these fields are depleted *gas* fields. It is important to mention that depleted *oil* fields have hardly been converted into underground gas storages because the mixture of gas, residual oil, and water results in a wide range of production and treatment issues. These issues and effects should be also considered when converting a depleted field into an underground hydrogen storage.

The injection- and withdrawal-rates depend on reservoir properties and the number of wells drilled. In many cases additional wells needed to be drilled during conversion, because the production strategy of a gas field during exploitation is different from a cyclic withdrawal and injection strategy of an underground gas storage.

Operations

To use a depleted gas field as an underground storage certain operational criteria must be met. Preferably good reservoir thicknesses as well as good petrophysical properties are required.

To achieve proper withdrawal and injection rates of the wells, the reservoir zones encountered need to have good and connected porosities and high permeabilites. The reservoir should also be positioned in a certain depth to allow a wide pressure range for the applicable and approved minimum and maximum injection and withdrawal pressures.

The porous storage layers should have a good lateral and vertical connectivity which leads to a good reservoir performance across the whole field. Any smaller scale layering of sediment layers could lead to fingering effects and results in inactive or dead zones. These effects can be drastic if the aquifer uses these sediment layers to bypass the gas saturated zones and flows directly into the well. The connectivity of the reservoir layers has also an influence on the appraisal strategy during the conversion of the depleted field. Therefore an extensive reservoir characterisation and reservoir modelling needs to be performed.

Suitable underground storages are not or only hardly faulted within the reservoir section, because the faults could act as either barriers which may split-up the storage formation in multiple compartments (compartmentalization) or as pathways to overlying strata.

Depending on the depth of the reservoir horizon a certain thickness of the top seal is necessary for full seal integrity. Preferably several additional sealing horizons exist in the strata above the storage horizon and give a full redundancy in case of any leakages.

Although depleted gas fields can provide huge in place volumes of gas, which may be similar to multiple cavern storage sites, the reservoir reaction curtails the operation and consequently the injection- and withdrawal-rates in relation to the cushion gas plus the numbers of turnovers, are smaller than at multiple cavern storage sites. This is because of the implications of the two phase flow in the complex porous structures. Therefore it is more likely to use depleted fields for a more seasonal gas supply than as fast-churn storages. The performance and flexibility of the depleted fields used for underground storage can be improved if horizontal wells, which produce from large reservoir sections, are deployed for the injection and production.

As described for the aquifer storages a higher mobility of hydrogen can be assumed leading to similar or higher volumetric withdrawal and injection rates compared to natural gas storage. However, due to the low density of hydrogen this results in about one tenth of the mass flow of natural gas.

4.2 Experience

Natural gas is successfully stored in depleted reservoirs, which is the preferred method in Europe and across the world since the early 20th century due to the large storage capacities that can be realised. The first depleted gas field that was converted to an underground gas storage was a gas field in the Welland County, Ontario in Canada and started operation in 1915 [4]. In 2008 there were 63 depleted fields present compared to 26 salt caverns sites (multiple caverns per site) and 22 aquifer storages in the EU area [35].

On the market for underground gas storages in Europe several cycles were completed in the past. These were always influenced by an increased need for energy as well as to by the intention to buffer the highly volatile gas-market where a lot of countries are dependent on a gas import. In general technology, experience and performance are mature in the area of the operation of underground gas storages in depleted gas fields with high safety standards as the basis for all operations.

So far worldwide no experience exists with the underground storage of **pure hydrogen** in depleted fields. In some fields **town gas**, a gas mixture of natural gas, hydrogen, carbon-dioxide, other gases and gas impurities, has been stored in the subsurface. This gas mixture is a refinery product of the coal gasification and was used for the local, urban gas-supply. In the past only limited research was performed to understand the geo-chemical as well as microbiological reactions and other subsurface processes in these reservoirs. In most cases the operated fields were converted in the 1960’s to 1970’s to natural gas storages. Two examples of depleted fields are provided in the following.

The natural gas storage at Uelsen in Germany was commissioned 1997 and is operated today by Storengy. During commissioning the working gas capacity was stepwise increased while more and more production wells were drilled [29]. The storage horizon is located in 1,500 m depth and provides 850 Mio m³(st) working gas which is connected by 7 production wells. Two wells which were used during the initial gas production phase prior 1997 are now utilised as observation wells. The storage can operate at a withdrawal rate of 475,000 m³(st)/h and an injection rate of 260,000 m³(st)/h.

One of the largest natural gas storages in Europe is located in Rheden, Germany. The formation produced natural gas from 1954 to 1992 and was then converted for gas storage and commissioning in 1993 by WINGAS. Additionally to the former production wells a number of 16 horizontal storage wells were drilled from 3 well sites. These wells provide a huge withdrawal rate of 2,5 Mio m³(st)/h and an injection rate of 1,5 Mio m³(st)/h. However, the relation to the immense working gas volume of 4,400 Mio m³(st) (cushion gas volume 2,950 Mio m³(st)) shows that the storage is operated with low flexibility.

Table 4-1: Depleted gas field storages

	Uelsen (Germany)	**Rheden (Germany)**
Geology	Detfurth-Sandstone	Zechstein/ Dolomite
Operator	Storengy	ASTORA (former WINGAS)
Stored fluid	Natural Gas	Natural Gas
Commission	1997	1993
Volume [m³]	-	-
Reference depth [m]	1,500	1,900 – 2,100
Pressure range [bar]	- 168	110 - 280
Possible working gas capacity H_2 Mio [kg]	750	4,200

Additional information about the storages listed in Table 4-1 is provided in Appendix A.

4.3 Geological Formations, their Occurrence and Potential

Depleted reservoirs consist of various combinations of different lithologies, different geological traps and different ages. A wide of formations are used across Europe for underground gas storage.

In *clastic reservoirs* the lithologies in underground gas storages are made of the following rock types:

- conglomerates,
- sandstones,
- shales and
- combinations of the above.

In *calcareous reservoirs* the lithologies are made of the following rock types:

- chalks as well as limestones,
- dolomites and
- combinations of the above.

There are also combinations of the clastic and calcareous lithologies possible. This has an influence on the connectivity of the reservoir rocks and the overall reservoir performance.

The underground storages can be distinguished in three different types of geological traps, see Figure 4-2:

- stratigraphic traps,
- structural traps or
- a combiniation of stratigraphic and structural traps.

This has again a strong influence on the reservoir connectivity and on the appraisal strategy plus on the reservoir performance.

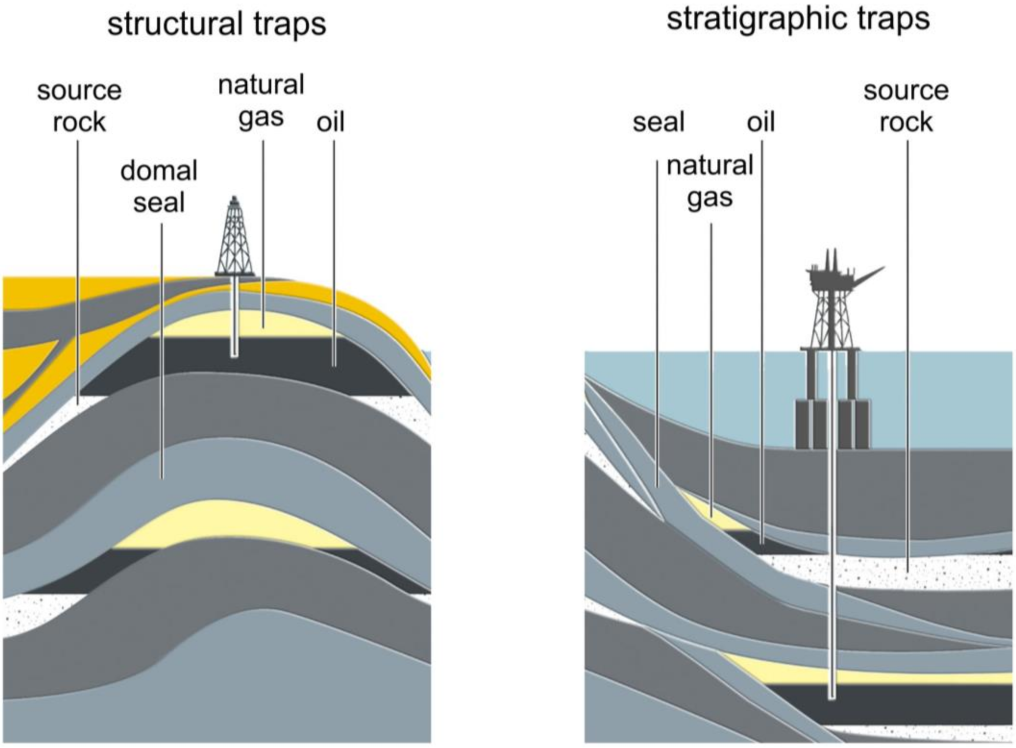

Figure 4-2: Classification of traps, [32] modified by KBB

The geological age and the formation of the reservoir rocks vary across Europe; they are mirroring the local depositional environments and the geological history. The geological age has in general no primary influence on the reservoirs as long as the petrophysical properties like porosity and/or permeability are not effected by secondary processes.

For an assessment of an underground gas storage it is necessary to evaluate all the above mentioned factors to get a full picture of the geological subsurface situation.

4.4 Feasibility

The worldwide experience with more than 400 depleted fields used as underground gas storages for natural gas and about one century of successful history demonstrate that it is feasible to store gas in the underground safely with limited impact for the environment. As mentioned there exists so far no experience with the underground storage of pure hydrogen in depleted fields with the exception of a few cases where hydrogen containing town gas had been stored. The storage of town gas showed in some cases an increased micro-bacterial activity which resulted in biological as well as geo-chemical reactions. Sometimes, this activity led to a consumption of hydrogen and conversion in methane as well as a production of hydrogen-sulphide [24].

To ensure continuous and safe operations after a potential conversion to hydrogen storages, it is required to perform full and integrated assessments of the processes involved in this conversion. This needs to include all geological and technical aspects of the reservoir itself, the issues related to the wells, well tests, the types of completion, the installed steel and used cements, workovers and surface installations as well as the interaction between the subsurface and the surface. Please note that this can only be seen as an incomplete short list of some prominent aspects.

The main focus must lie on a safe and secure operation with no or only minimal environmental impact. Because of the wide range of aspects for future hydrogen storage applications it is necessary to perform research projects or smaller scale demonstration projects to fully understand the processes and to assess the possible risks of underground hydrogen storage and develop mitigation plans for any of these risks. Due to the complexity of the problems and the currently missing experience there might be longer periods of research and development required before any proven and safe verification of the underground storage of hydrogen in depleted fields is possible.

Only few depleted oil fields are utilised for natural gas storage today because of several reasons. Some of these reasons will also influence the decision to choose depleted oil fields for future hydrogen storage:

- During operation of depleted oil fields residual oil may periodically be produced and increases the operation and maintenance efforts of the storage.
- Large contents of natural gas can dissolve in the residual oil and becomes unrecoverable. This loss of investment might also occur for hydrogen.
- In case of depleted gas fields mixing of natural gas and hydrogen will decrease with increased amount of hydrogen injected. However, in depleted oil fields the remaining residual oil will evaporate into the hydrogen for much longer durations.

4.5 Characteristic and Performance

Similar to aquifer storages the sizes of depleted fields vary widely. However, the size of the storage is not scalable. Typical reservoir properties of fields converted to storages are porosities of 15 % to 30 % and permeabilites around 2,000 mD. Depleted fields are commonly found in a depth range of several hundred meters to less than three-thousand meters. The average working gas volumes range between one million m^3 to several thousand million m^3, at a minimum pressure regime between ten bar to couple of tens of bar up to maximum pressure regime of several hundred bar [35].

Like aquifers depleted fields provide only reduced flexibility and commonly perform only one turnover per year. The rates depend on the permeability and complexity of the storage formation and also the number and performance of the production wells depending on the specific site. For natural gas withdrawal and injection rates from 80,000 kg/h (100,000 m^3(st)/h) to more than e.g. 800,000 kg/h (1,000,000 m^3(st)) are feasible for large storages like Bierwang operated by E.ON Gas Storage. One can assume the same volumetric flow rates for hydrogen. Therefore mass flow rates of 8,000 to 80,000 kg/h seem to be feasible for hydrogen.

High contents of water and impurities must be removed from the withdrawn gas, depending on the specific storage. Therefore gas treatment processes need to be applied correspondingly.

5 Conventionally mined Rock Caverns

Conventionally mined rock caverns are underground cavities drifted using conventional mining techniques (shaft sinking, excavation of cavities by blasting or cutting). Mined rock caverns can be constructed in a certain range of geological formations which need to allow for the construction and operation of large, long term stable caverns. These formations need to be either widely intrinsically tight, which can be intensified by the existence or introduction of water, or made tight by installing an engineered lining.

Rock caverns have been developed for the storage of liquid hydrocarbons like oil, gasoline and liquid petroleum gases. Most of these developments have been performed in Scandinavian countries, since they provide the suitable rock formations in large homogenous quantities. Additionally, rock cavern storages for liquid hydrocarbons have been constructed in the US, Saudi-Arabia and East Asia. In a special application a rock cavern has been used for a small sized high pressure natural gas storage in Sweden (Skallen) and a very large but also very specific storage in Czechia (Haje).

The initially developed and still applied sealing concept of rock caverns bases on the fact, that typically the required strong and competent rocks provide fractures and fissures and are therefore not tight against liquids (and gases). This, on the other hand, leads to an inflow of water, if groundwater is present or water is artificially provided and if the storage pressure is kept below the water column pressure. The impressed water flow then provides the tightness of the storage, as described below in-detail. However, additional sealing technologies have been developed and are described in the following chapter.

5.1 Description of Technology

Rock caverns are drifted using mining methods. This means that they require one or more access drifts (ramps) or shafts to deliver technical equipment, haul the excavated rock, transport personnel and enable the ventilation.

In case ramps are utilised they will be used by trucks and therefore need to have an appropriate cross-section, which, depending on the logistics involved, have either two lanes or one lane with lay-bys to allow traffic to pass in both directions. The gradient of the ramps has to be kept low enough to enable vehicular use. A ramp can be constructed in the form of a spiral if the storage is to be constructed at a significant depth. Alternatively one or several vertical shafts can be either drilled or sunk using conventional mining methods. In both cases it may be necessary to implement stabilisation methods (grouting or freezing) during the drifting of the access routes depending on the geology.

The geometry of the storage cavity has to take into consideration geological and geomechanical design criteria, and this determines the excavation method. Drifts with circular cross-sections can be drifted using full face tunnellers (tunnel engineering) or by drilling and blasting. Gallery caverns are also drifted by drilling and blasting but the material can be removed in some horizontal layers which enable the construction of higher caverns. Cylindrical caverns are constructed by using blasting techniques to drift the roof and floor zone followed by the construction of a vertical pilot shaft to connect the upper and the lower zones. Blasting is then undertaken to expand the pilot shaft laterally to the specified size. Damage to the remaining rock fabric should be kept to a minimum during blasting. This is especially important for the access shafts and drifts and the planned walls of the cavern.

In general, the host rock must be strong enough to enable the construction of a self-supporting cavern which is large enough to be economical. Rock bolts can be driven several metres into the rock during the construction of the cavern to prevent blocks of rock from falling of the roof. And shotcrete can be sprayed on to the cavern walls to stabilise unconsolidated rock, and additional cement can be injected into the cavern walls if necessary via short boreholes (grouting).

Because of the limited possible cavity size for rock caverns it is common to combine multiple drifts or multiple caverns by internal shafts or centralized access shafts or ramps.

Common rock caverns that are applied to store liquid hydrocarbons only need to prevent or control inflow of ground or surface water into the storage and leakage of the product through the storage walls. For high pressure gas storages one has to consider the tightness of the storage walls and additionally the tightness of the access shaft or ramp, which requires the installation of plugs as extra structures.

Seal of access shaft or ramp

The following describes the technology to seal the access to the cavity against the storage pressure, based on the few yet realised rock cavern and abandoned mine storages as well as on theoretical studies.

Seals at the access drifts of the shafts are the most sensitive points of the storage, which is why complex seals are necessary. These have to be as deep as possible within the rock and must become integrated with the rock to be able to optimally transfer the forces produced by its intrinsic weight and the pressures and pre-stresses into the rock. In addition, seals should be located in zones where the surrounding rock is as undamaged as possible, particularly strong, and has low permeability.

Conventionally, shaft constructions are used in which the properties such as strength and frictional bonding with the rock, as well as tightness to prevent the migration of gas, are guaranteed by installing various structural components. Structures of this kind documented in the literature include one or more reinforced concrete plugs supporting an overlying or intermediate seal [3], [2]. The plug absorbs the associated forces and transfers them radially into the rock via interlocking boundaries. To prevent damage to the contact surfaces of the abutments and the rock mass over the long term, despite the dynamic loads, slight low-friction layers are incorporated. Permanent sealing is guaranteed by pressing the plug down permanently against the pressure of the storage. This involves enclosing a liquid and, for instance, a liquid column, to permanently maintain overpressure with respect to the storage and any groundwater which may also be influencing the overall set-up. This causes the seal fluid to infiltrate any fractures or fissures which may be present, and to seal them by virtue of its high viscosity [23].

The connection pipes required to inject and produce the gas can be laid through the sealing structure (e.g. at the abandoned salt mine Bernburg), although this is technically complicated and represents additional risk to the permanent sealing of the structure. Another option is to drill wells, cement them in the rock, and equip them with a classic gas production completion including a subsurface safety valve (as done at the Haje facility) as already described in section 2 on salt caverns [3].

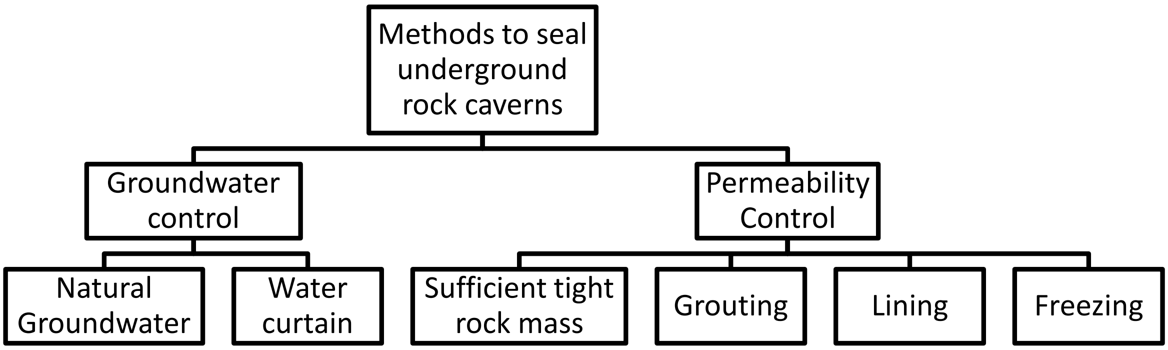

Figure 5-1: Methods to limit or eliminate gas leakage from a pressurised underground storage, after [14]

Seal of storage wall

The host rocks in which rock caverns can be constructed are normally not adequately tight to store liquids or even gases under high pressure. This also usually applies to rock types which benefit from low permeabilities because the mechanical stresses in the rock mass or tectonic movements can lead to the development of fractures or faults. However, the rock can be sealed up using a range of different methods. These methods are listed in Figure 5-1 and can be subdivided into those which are sealed off with the help of groundwater or by controlling the permeability by either exploiting it or by installing a lining with suitable low permeability. By installation of such lining the storage seal becomes independent of the permeability of the host rock.

Very few rock types are intrinsically tight to store gaseous media. Additional sealing can be established by using the groundwater naturally present in the storage horizon. This enables pressures to be achieved which allow the storage of liquid hydro-carbons with low vapour pressures (petrol, diesel, kerosene). The storage of media with higher vapour pressures such as liquefied petroleum gas (LPG), natural gas or hydrogen, usually requires the implementation of targeted groundwater management (water curtain) or the installation of a lining to additionally seal off the rock mass.

The host rock has to have a very low permeability to be able to operate the storage merely on the basis of **sufficiently tight rock mass** and without making use of any of the additional sealing methods. It is also essential in such cases that there are no open fissures or faults near the planned underground cavity. It is also not adequate to use rock formations which contain no fractures in their original state. It is more important that the primary tightness of the rock mass remains un-violated by the long-term operation of the storage. Groundwater is usually used as an additional seal because the aforementioned conditions are rarely encountered in the real world for the reasons described above.

The **groundwater control** method involves maintaining an internal cavern pressure below the natural prevailed water pressure within the rock mass to engineer a continuous slight inflow of water into the cavern. This prevents gas from escaping from the cavern via any minor fractures which might be present. However, when using groundwater control it is essential that the water pressure in the walls of the cavern has a negative gradient towards of the cavern for every potential migration path to ensure that the product is always forced back into the cavern. The water flowing into the cavern during groundwater control collects at the deepest point of the cavern and is pumped out by borehole pumps either continuously or at intervals when the level exceeds a certain level. Amongst others Liang and Lindbloom carried out investigations on the maximum possible storage pressure achievable in caverns which are sealed by groundwater (natural groundwater as well as water curtains), see Liang et al [19] as well as Zhonkui et al. [31]. Generally, gas escapes when the storage pressures reach more than 70 – 80 % of the hydrostatic pressure.

The **water curtain** method can be used if the natural groundwater present is inadequate to saturate the host rock and realise the seal, or if the storage pressure is to be increased. The water curtain method involves drilling wells above and to the side of the cavern and injecting water into the rock mass, see Figure 5-2.

This effectively saturates the rock mass with water around the storage. Some of the injected water flows into the cavern and some remains in the rock mass or flows into other zones. Water therefore needs to be injected continuously during operations to seal the storage. The water injection not only establishes the hydrostatic pressure, but also achieves a hydrodynamic pressure which is dependent on the volume of water and the paths along which the water flows. Boreholes have to be drilled at intervals of 5 to 20 m depending on the geology if the water pressure is to be raised significantly above the natural hydrostatic groundwater pressure, so that higher storage pressures and densities can be achieved [14].

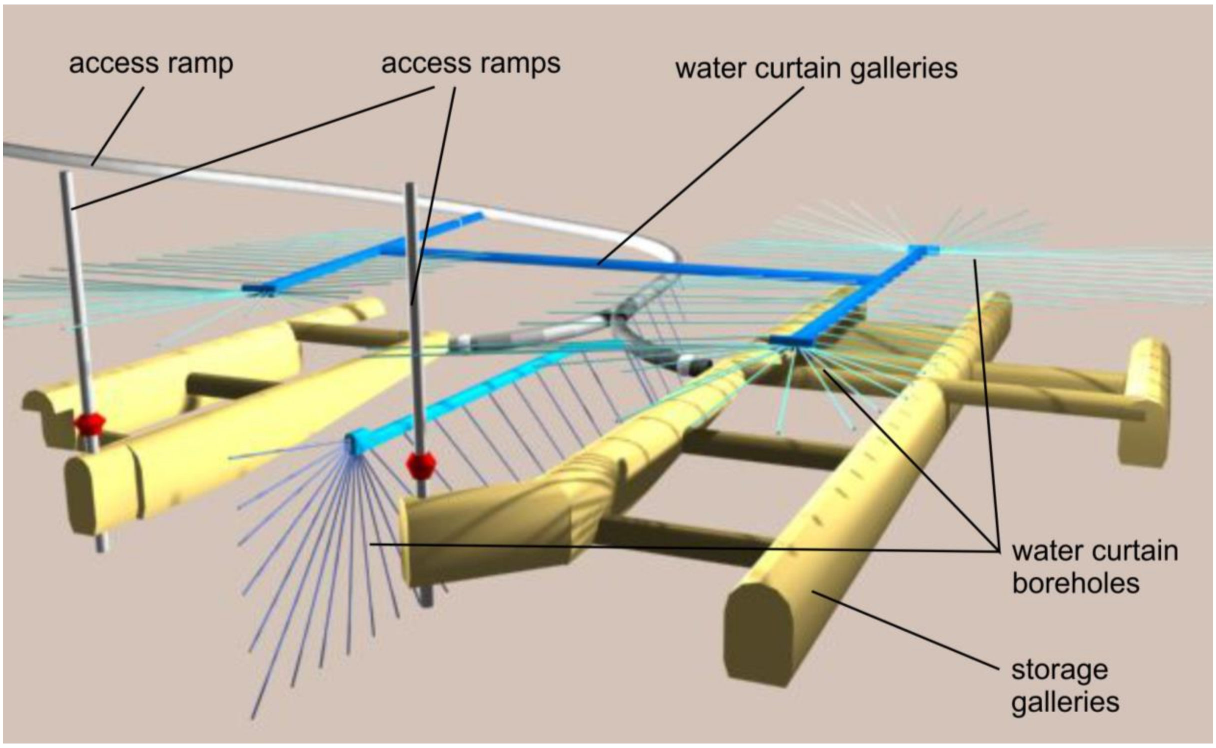

Figure 5-2: Storage galleries and water curtain of LPG storage, after [36] modified by KBB

The costs for creating the water curtain boreholes can be reduced by drilling them from either a central chamber or a gallery above the storage, see Figure 5-3. Grouting by injecting cement into the wall of the cavern reduces the fractures in the rock mass thus having a positive effect on the tightness of the cavern, which therefore also reduces the amount of water inflow and raises the hydrodynamic pressure. The amount of water required to seal the cavern field can also be reduced by laying out several caverns next to one another.

Intense water injection in some cavern storages enables the hydrostatic pressure to be doubled. It is naturally crucial that the rock mass is not fractured by raising the water pressure too much because this can damage the storage seal. Another problem is that water curtain wells may be blocked by particles or biological or chemical deposits when they have been used for a long time. It is therefore important to use water of adequate quality, as well as to add inhibitors in some cases.

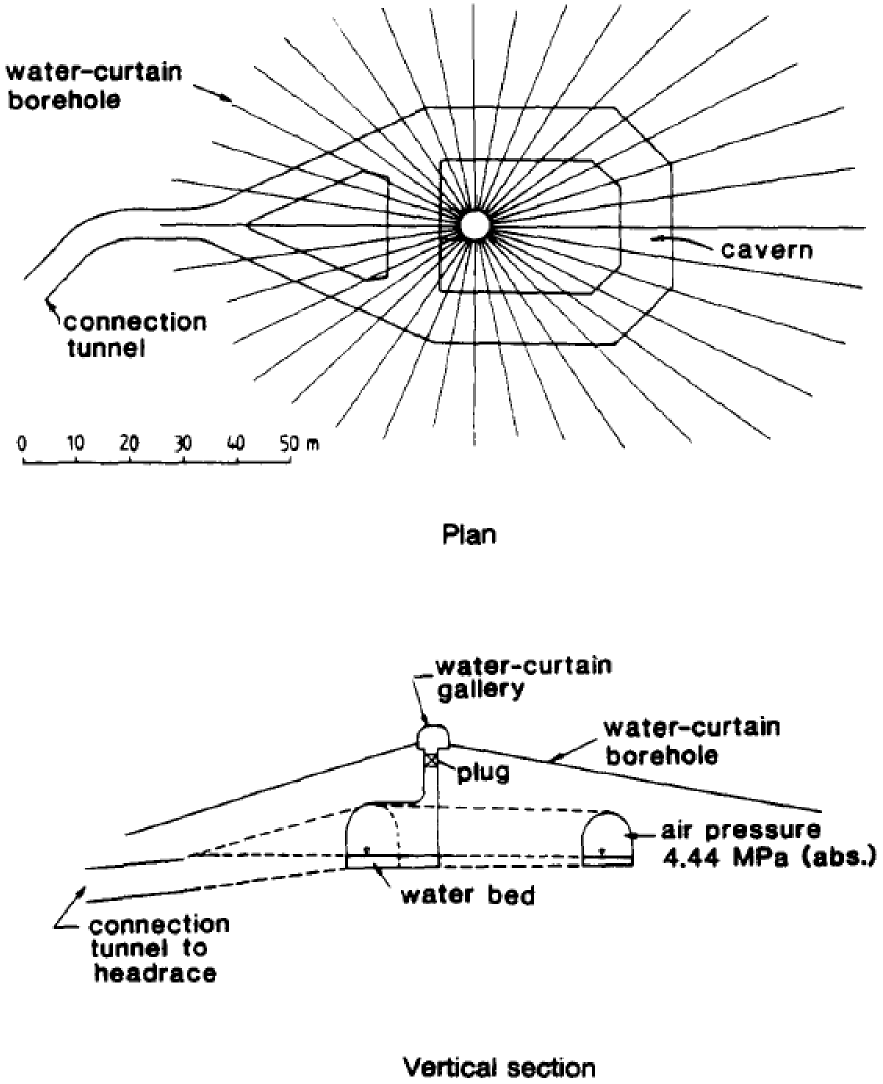

Figure 5-3: Water curtain of an air pressure cavern constructed for a hydro power project [14]

The geometrical storage volume can be used optimally in some storage media by using the **refrigerated cavern** method (freezing): this involves cooling down the storage medium prior to emplacement so that it condenses and therefore undergoes an immense decrease in specific volume. The storage in this case is cooled down by partial evaporation of the storage medium itself (boil off). The storage pressure must be lower than the hydrostatic pressure in this case. Because of the extremely low temperature of liquid hydrogen (13.8 – 33 K) storing liquid hydrogen of this kind would be extremely energy-intensive and probably therefore uneconomical. Cooling down the cavern to below the freezing point of the groundwater may be a feasible way of strengthening the sealing effect although this is only rarely discussed in the literature. For the aforementioned reasons, sealing a cavern this way used for the storage of hydrogen would involve installing cooling pipes within the rock mass and continuously cooling the rock. This would also be associated with enormous costs and would therefore be uneconomic. The operation of refrigerating technologies is therefore not discussed further in the following.

As shown in the diagram in Figure 5-1, the tightness of a storage can also be achieved by installing an engineered **lining** (lined rock cavern, LRC). The lining could be a polymer membrane (e.g. polypropylene) or corrosion-resistant stainless steel of adequate thickness. However, these linings are just one element of the compound layers necessary to build the cavern wall. This is because the surface of the rock may need to be stabilised and smoothed to prevent long-term damage to the lining as a result of deformation of the cavern.

Depending on the geology, cavern wall construction may involve installing rock bolts or grouting the rock mass. In addition, shotcrete can be used to smooth the surface of the cavern before installing the lining (whose thicknesses depends on each given situation), and joining up the individual lining components (slabs, membranes) to create a gas tight seal, see Figure 5-4. Constructing a layered cavern wall enables the stability and tightness criteria to be satisfied by a range of different components. This means that the actual sealing layer made of steel or polymer membrane does not have to be very thick.

Alternatively, a steel structure made from reinforcing struts and steel plates can be constructed step-by-step followed by successive cementation of the annulus between the steel structure and the rock mass. The thickness of the steel plates used in this method needs to be larger than in the multi-layer concept.

For both concepts groundwater has to be kept away from the storage to avoid corrosion and to prevent buoyancy forces acting on the cavern. The penetration of water could also force the lining away from the cavern wall.

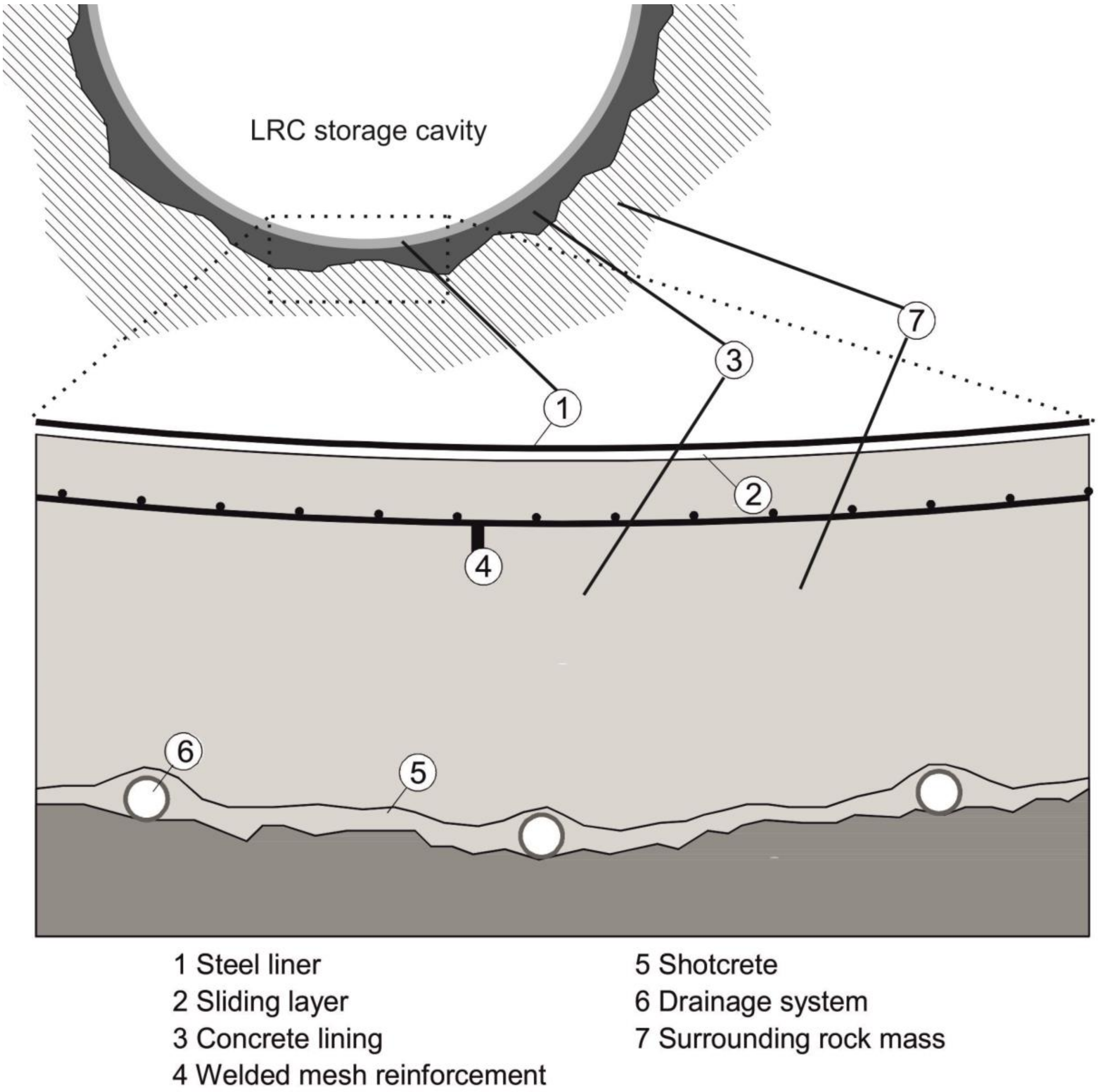

Figure 5-4: Schematic of lined rock cavern wall, after [12] modified by KBB

There are no known **test methods** to reliably verify the tightness of unlined rock storages. Unlike salt caverns and depleted oil and gas fields, it is not possible per se to assume the tightness of a host rock or the surrounding geology. A test therefore needs to encompass the whole test volume. Furthermore, the integrity test also has to be carried out with a test gas with a comparable viscosity, like e.g. air or Nitrogen. Obviously this requires efforts of month or years when large mines are supposed to be tested with similar accuracy than common for salt caverns.

When the cavern is being filled for the first time, the air present in the cavern after completion must be replaced by the storage gas. To prevent the formation of a flammable or explosive mixture, the cavern can be flushed first with an inert gas like nitrogen to displace the oxygen before filling the cavern with hydrogen for the first time. Flushing is carried out under minimum pressure to use the smallest possible amount of gas. Another alternative could be to flood the storage with water which is then displaced by the hydrogen during gas first fill operations. This also enables to perform a hydraulic pressure test with water.

The amount of time required to construct the storage can vary considerably depending on the type of rock and the excavation method. Construction of the pilot project in Skallen described later on in this report took around four years, of which two years were required to drift the caverns and two years to install the lining. Since on-going research on construction methods, materials and demonstration activities took place during construction it is assumed, that subsequent storage projects will require a significantly shorter time for construction.

Operating procedure

The caverns are operated in pressure slide mode between the maximum and the minimum pressure. This therefore subjects the host rock and the various layers in the cavern wall, to cyclic stresses. The low elasticity of the crystalline rock mass can cause the development of fractures in the cavern wall under these cyclic loads, which is part of the storage concept. The composite wall is specifically designed to distribute the fractures in the desired pattern in the concrete component so that the gas-tight steel lining is never load-supporting or strained above its accepted elastic level. This is maintained by a pressure rate limitation derived by the mechanical properties of the rock mass.

A supporting pressure or cushion gas pressure is required to maintain cavern stability, as well as to avoid the inflow of excessive volumes of water if the water curtain technology is used. This minimum pressure can be much lower and the maximum pressure much higher in an LRC than in other storages because strains and fractures can safely be distributed to the host rock, such that the gas tight steel lining is never load supported or submitted to high strains.

A maximum pressure change rate must be complied with during gas first fill and later operation to also prevent the temperature from changing too strongly. The initial formation temperature is relatively low at shallow depth compared too much deeper lying salt caverns or pore storages. Moreover, thermal conduction between the gas and the rock mass is either inhibited by several layers of different materials, or the water continuously circulating around the cavern when implementing the water curtain method acts to cool down the storage. This means that temperatures below zero degree are certainly possible during longer or intense withdrawal periods. Caverns which are sealed off by water are also likely to give rise to higher water saturations in the hydrogen, which means that temperatures below 0 °C should be avoided to prevent the formation of ice. Moreover, the expansion in volume of the water which freezes in the cavern wall can enlarge fractures within the wall of the cavern. Temperature fluctuations of this kind must therefore be avoided at all costs. However, in the case of an LRC, it is very unlikely that the formation of ice will hinder the operation of the storage because of the dry storage space.

In caverns which are sealed off by water, it is possible for the hydrogen to be contaminated as a result of biochemical reactions. The impurities of the gas must be reduced by operation of above ground gas installations. The high flow rate of the water in such storages can also give rise to high humidity levels in the stored gas which in turn requires the installation of drying plant on the surface. The engineered walls of an LRC exhibit an advantage because they prevent contamination by chemical or biological reactions or the absorption of water. This means that surface installations to dry and purify the gas are not needed in such cases.

The tightness of an engineered lining can be monitored by sensors installed behind the seal. In all types of rock cavern storages, additional sensors can be installed to monitor the integrity of the storage, the pressure and temperature of the storage medium, and the stress state of the host rock.

The liquids sealing the shaft sealing structure must always be maintained under a defined pressure: this can be achieved for instance by establishing a liquid column in a riser or within the whole shaft.

5.2 Experience

Projects for the storage of liquid hydrocarbons in unlined rock caverns have been pursued in the USA in particular, and in Europe (especially Scandinavia) since the 1950s. A large number of caverns with a geometric volume of around 80,000 m³ each were created. Some of the storages were affected by problems caused by bacterial contamination (foaming, disintegration, degeneration) – these problems have been solved, however.

A storage in a limestone formation was constructed in **Gargenville** in France. Storage operations began in 1972 with the storage of liquid hydrocarbons, but the caverns were then converted to store propane in 1977. The storage was shut down in 2010 [20].

RWE Transgas operates a storage cavern in **Haje**, Czech Republic to store natural gas, see Figure 5-5. The storage cavern uses groundwater control to maintain tightness in a granite formation. Commissioning took place in 1998 after investigating and testing the geology in the 1980s. An existing mine shaft was used which enabled the storage to be constructed economically at a depth of 950 m. The whole floor of the cavern has a slight gradient to enable inflowing groundwater to flow to the deepest part of the cavern where it is pumped out by submersible pumps. The underground workings were constructed specially for the storage project using the drilling and blasting technique, see Figure 5-6.

The caverns have a cross-section measuring 12 to 15 m² and a total length of 45 km. The published value of the working gas volume was used to derive a minimum pressure of roughly 38 bar, see Table 5-1. The water table is around 850 m above the base of the storage which corresponds to a hydrostatic pressure of 83 bar. However, the storage is operated at a maximum pressure of 125 bar which means that the hydrostatic pressure is exceeded by around 50 %, even though no water curtain is used around the storage cavities. Water is only injected around the sealing structure. The literature reports the construction costs as being around € 92 Mio [3]. These costs are almost certainly well below realistic construction costs at today’s prices because the cavern was originally constructed when the Czech Republic was a socialist state. More realistic costs can probably be interpolated from the study discussed in the following which assumes a similar geology and also involved the construction of underground drifts.

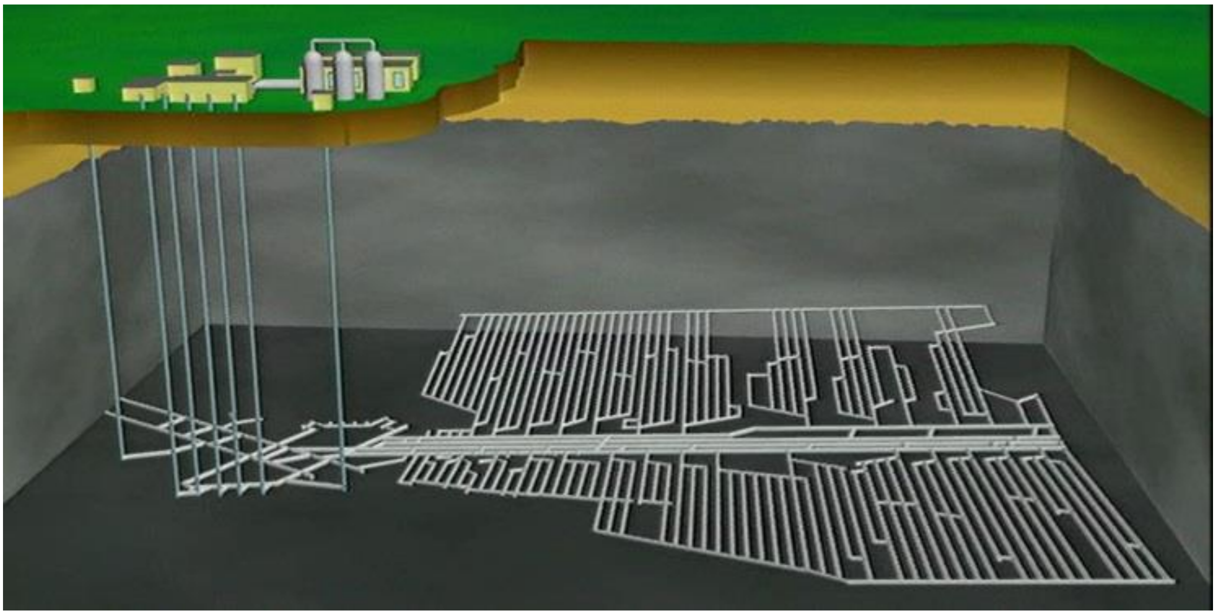

Figure 5-5: Schematic of Haje rock cavern storage [40]

Figure 5-6: Photography of Drill and Blast driving in Haje [40]

The **Sandia feasibility study** prepared by S. Bauer et al [5] includes a cost estimate and describes a compressed air rock cavern proposed to be constructed in granite which involved the drifting of the underground workings and sealing with a water curtain. Investment costs of € 319 Mio are reported in the study which is considered here as representative for the storage of natural gas and hydrogen, see Table 5-1.

A lined rock cavern as a prototype for natural gas storage was constructed in **Skallen**, Sweden, see Table 5-1, Figure 5-7 and Figure 5-8. The storage is located on the side of a mountain and connected to the surface via a vertical shaft and an inclined access drift. The cavern has a cylindrical shape and a diameter of 35 m and a height of 52 m [9]. The costs for the project were not reported but can be interpolated from the costs of the study discussed in the following.

Figure 5-7: LRC Skallen, photography of partly excavated cavern [41]

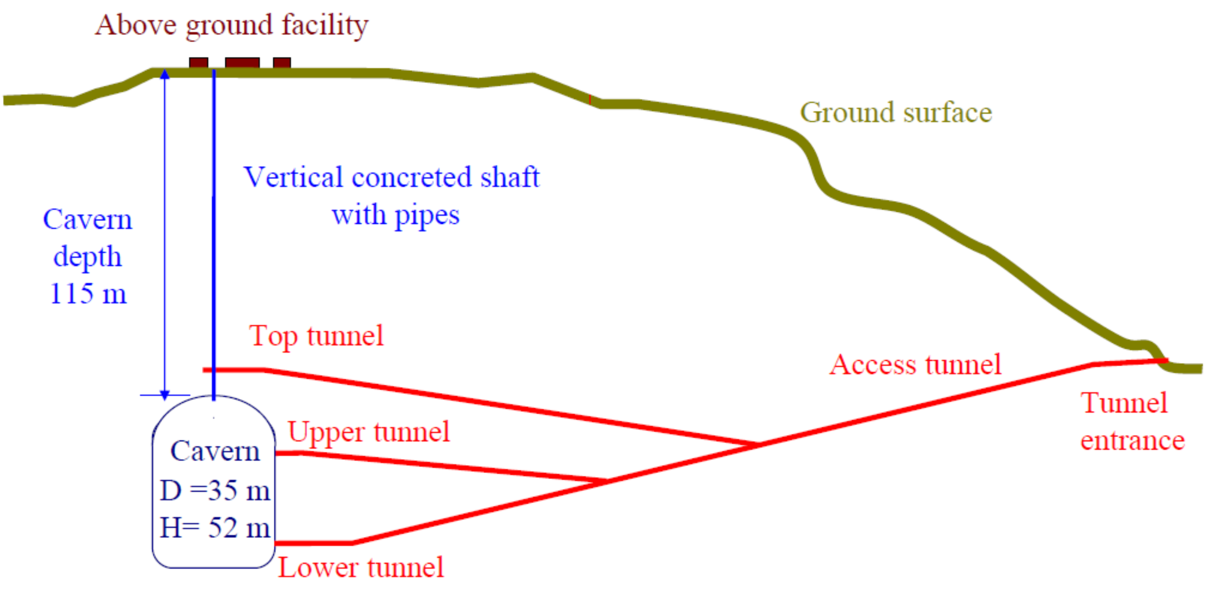

Figure 5-8: LRC Skallen schematic of cavern setup (bottom) [41]

A study prepared by **Sofregaz** describes the commercial potential of LRCs using a concept analogous to the Skallen project and involving the construction of four caverns from shared spiral access drifts [28]. The optimised use of the access drifts is intended to reduce their share of the costs in relation to the storage volume and to therefore make the storage more economical.

Table 5-1: Rock cavern storages (studies and realised projects)

	Haje (Czech Republic)	**Sandia Study**	**Skallen (Sweden)**	**Sofregaz 4 LRC Study**
Geology	Granite	Granite	Gneiss	-
Operator	RWE Transgas	-	E.On Sweden	-
Stored fluid	NG	Air	NG	NG
Seal/Lining	Ground water	Water Curtain	Steel	Steel
Commission/ operation	1998	**Study**	2004	**Study**
Volume [m³]	620,000	1,010,900	40,000	320,000
Reference depth [m]	950	600	115	-
Pressure range [bar]	38 - 125	30 – 60	10 - 230	38 - 200
Possible working gas capacity H_2 Mio [kg]	3.78	2.32	0.64	4.34

Preliminary studies are currently being elaborated for an analogous project in Innertkirchen in Switzerland which also involves four caverns; however, no further data has been published on this project so far.

There are currently no rock caverns constructed for the storage of **hydrogen**.

Appendix A contains additional information on the storages described in Table 5-1. The figures quoted in the table and the appendix base on the reported volumes and pressures, which were then used to interpolate the data for natural gas and hydrogen.

5.3 Geological Formations, their Occurrence and Potential

The basic prerequisites for rocks suitable for cavern construction are a massive, homogeneous texture with minimal primary textural or structural weaknesses, low permeability, and superior mechanical stability. Rocks that generally comply with these requirements are certain sedimentary rocks, massive carbonates as well as igneous or metamorphic crystalline rocks (e. g. granite, gneiss).

Most crystalline rocks found at the surface or at shallow depths today were formed in mountain building events at active continental margins, i.e. by convergence of two of the Earth’s crustal plates. In particular, Europe has been affected by three such mountain-building events during the past 450 million years. These events are termed the Caledonian (450 to 400 million years before present), the Hercynian (350 to 300 million years b. p.), and Alpine (100 to 50 million years b. p.) orogenies. Mountain building processes not only uplifted rocks, but have also altered their properties by metamorphosis. Rock metamorphosis considerably increases the tightness of rocks.

The most widespread and most typical examples are the extensive outcrops of Caledonian crystalline rocks that make up the majority of Scotland and north-western Scandinavia. Adjacent central and eastern Scandinavia, comprising similar crystalline rocks, belong to the Baltic shield, represent a stable old continental crust segment formed by metamorphic rocks. Smaller occurrences of mainly Hercynian crystalline rocks that may strongly vary in thickness and extent are scattered across Europe. Crystalline rocks of Alpine age occur within the central parts of the Pyrenean, Alpine, Apennine, and Carpathian ranges.

The principle of rock cavern construction is usage of the rock mass as the main construction material and utilizes the self-supporting property and load bearing capacity of crystalline, magmatic and metamorphic rock types [12].

5.4 Feasibility

Only a few rock caverns have been used to store natural gas to date, and none have been used to store hydrogen. However, the two successfully realised natural gas storage projects may be considered to discuss the feasibility to apply conventionally minded rock caverns for hydrogen storage:

- the shallow lined rock cavern prototype in Skallen and
- the very deep laying rock cavern in Haje, which is sealed by a combination of very deep lying granite and groundwater management

The following therefore discusses general aspects and comments on this storage option.

5.4.1 Health, Safety and Environment

The construction of rock caverns is associated with a higher level of accident risk then for salt caverns and porous storages because of the use of mining techniques to excavate the caverns: such as drilling, blasting and clearing the fallen rock. The excavation work naturally takes place in constricted and poorly accessible places inside the cavity and therefore bears larger risks than for salt cavern or pore storages, where all work steps are performed at the surface.

When using groundwater management to seal an underground storage, it is not possible to completely exclude the possibility of gas leakages, for instance, as a result of operational malfunctions. Under these circumstances, gas can migrate to the surface where it could be ignited. It may be possible to find locations which benefit of a second sealing formation above the storage to provide an additional level of safety. In such cases, it is also vital to establish whether the escaping hydrogen could enter horizons permeable to gas, or faults, and could thus potentially migrate into inhabited zones or areas used for other purposes. This hazard can be almost completely excluded in the case of lined rock caverns if suitable materials are selected and when storage operations are also monitored by sensors.

The storage component exposed to the highest stresses is the structure which seals the cavern shaft. Total failure of the overall structure is unlikely, however, because of its integration within the rock mass. The failure of the plug in this case would lead to an enormous flow of hydrogen into the surrounding area because of the large diameter of the shaft. Leaks bypassing the sealing structure cannot be completely excluded; however, they can be detected by monitoring the plugs.

Some of the existing rock caverns are operated via specially drilled access boreholes. Damage to the production wells could lead to a blow-out of the storage. This risk can be almost completely excluded, however, by installing subsurface safety valves.

Large volumes of waste rock are produced during the construction of the cavern which have to be removed in an environmentally-friendly way and then either disposed of or recycled. This involves a large number of journeys by truck. In addition to this extra traffic, construction is also associated with emissions of construction noise or vibrations within the ground. Further issues may occur if the excavated rock mass is contaminated with heavy metals or other hazardous materials.

The watertable around a cavern is influenced by the operation of a water curtain as well as when using the natural groundwater. This can have an impact on the watertable in some distance to the storage also.

5.4.2 Required R&D

Because only a few rock caverns have been used to date for the storage of gases under high pressure, and none of these caverns is used for storing hydrogen, it is not possible to fully assess the amount of research and development work still required.

The long-term stability of the storage must be verified by undertaking specific laboratory tests because damage can no longer be assessed in situ after sealing the storage.

In all of the storage options considered here, materials must be identified for the sealing structure, as well as for the production wells, which are resistant to hydrogen corrosion, and sufficiently tight. In the case of LRCs, the materials (polymers, steel) have to be impermeable to hydrogen and resistant to hydrogen embrittlement. If the accumulation of hydrogen behind the lining cannot be completely excluded, the steel used to stabilise the structure (reinforcement) also needs to be hydrogen-resistant.

Only very few gas storages have been constructed in **limestone** (e.g. Gargenville, see Chapter 5.2) [20]. The permeability of lime stone varies in a broad range and only few occurrences may be utilised to store high pressure gases. Therefore specific exploration and testing is required to get information about the suitability of formations.

The **water curtain** technology has not been applied to seal off a hydrogen storage so far as yet documented in the literature. Because of the higher mobility of hydrogen compared to natural gas, tests need to be carried out to determine the maximum pressure differences at which such storages can still be considered to be technically tight.

Depending on the specific host rock, **chemical or biological reactions** could potentially cause contamination of the stored hydrogen. The reactivities of the rock types and each location can, however, be investigated and determined.

It may be necessary to develop new testing techniques to confirm the **integrity** of these gas storages.

5.4.3 Costs

A large part of the costs is accounted for personnel costs for the excavation of the underground cavities using mining technology. These personnel costs are dependent on the salary level of the country or region in which the storage is to be constructed and therefore independent of the storage media.

The construction of a lining gives rise to additional personnel costs as well as significant material costs which can vary strongly depending on the thickness and the specific material involved. The use of the investment costs reported in [28] is considered to be sufficiently accurate without any modification for the purposes of this study. However, lacking of information makes it hard to estimate the operating costs.

Higher costs are almost certainly involved, however, for the operation of the water curtain. Operating lined rock caverns is much cheaper, particularly because the gas does not need to be dried or purified.

The costs for an unlined rock cavern and a lined rock cavern are summarised in Appendix A based on the experience from the projects discussed in chapter 5.2.

5.4.4 Risks

It is not possible to completely exclude a potential leakage of stored gas from caverns sealed using the water management technology, see also Section 5.4.1. If the seal fails, gas will escape via fractures in the rock mass and rise upwards. It may be possible to find locations which benefit from a second sealing formation above the storage and which therefore reduce the associated risks.

The risks of leakage from an LRC are much lower. And because the sealing concept is independent of the material, the differences between the storage of natural gas and hydrogen are considered to be low.

The geological risk for an LRC is much lower than for a salt cavern because the rock formation only has to provide the necessary stability for the LRC and not contribute to the tightness. Nevertheless, unforeseen geological structures (e.g. dykes) could represent weaknesses in the cavern wall and therefore jeopardise storage projects involving all of the different storage types discussed here.

5.5 Characteristic and Performance

Rock caverns can reach large volumes (up to 1 million m³) if several galleries are drifted; however, lining with steel plates cannot be applied for this kind of storage and the in-situ of the host rock is questionable.

Lined rock caverns have been realised with a volume of 40,000 m³ each, while studies propose feasible volumes of up to 320,000 m³ by combining several cylindrical caverns. Lined caverns can withstand pressures of up to 230 bar or even more, depending on the strength of the host rock mass and the corresponding specific cavern wall design. Furthermore, their very small minimum pressure requires only a small amount of cushion gas. By opinion of an expert in lined rock cavern construction[3] single caverns with a volume of 120,000 m³ and pressures ranging from 20 – 220 bar are feasible. Such a cavern would reach a working gas of 1.7 Mio kg hydrogen (22.5 Mio m³(st)) with only 0.2 Mio kg (2 Mio m³(st)) of cushion gas.

Because lined rock caverns are less dependent on the host rock, pressure rates higher than for rock caverns and therefore more gas turnovers per year are feasible.

[3] Personal communication with Gérard Durup, 06.03.2013

Based on the data of Skallen natural gas rates of 42,000 m^3(st)/h or 35,000 kg/h can be realised. These rates can probably be increased for larger storage volumes and may be multiplied by the number of caverns, if a concept like the Sofregaz Studie is realised. Since similar thermodynamic and rock mechanic limitations occur for salt and for lined rock caverns a hydrogen mass flow of one tenth the natural gas mass can be assume for LRC also. Therefore the possible hydrogen rate, related to the Skallen storage would be 3,600 kg/h.

6 Abandoned Conventional Mines

The following describes the use of conventional mines for hydrogen storage purposes which were originally used for the extraction of natural resources as e.g. salt, ore, coal or limestone and have now been abandoned ore are about to be abandoned.

There are numerous abandoned conventional mines in various types of geological formations in Europe that were not or only partially backfilled and which therefore could theoretically provide plenty of storage volume for the storage of gaseous media like hydrogen. These mines provide medium to large geometric volumes are often at depths between a few hundred metres to 1,000 metres or even deeper. This means that they are in general at a depth range suitable for the operating pressures required for hydrogen storage.

Unlike rock caverns, the abandoned mines were not constructed with the intention of storing gas, but to extract natural resources. The size and layout of the underground workings to be used for storage are therefore given, and cannot be changed very much. This means that the most important step to realise such a storage is the selection procedure to choose a suitable mine.

The storage option abandoned mines is very inhomogeneous because of the different geology in which the mines were excavated and the different techniques that were applied to excavate the cavities. However, for all of these varieties the approach to select between the already existing potential storage spaces is common. This should be done by considering the need to construct a sealing structure in the existing shafts. If necessary, the underground workings may be tightened e.g. by water curtain technology.

No hydrogen storages, and only a few natural gas storages, have been constructed to date in abandoned mines.

Costs are fairly low because of the utilisation of existing mines and infrastructure. However, converting abandoned mines into storages could be associated with very high risks under certain circumstances because the tightness of the storage cannot be realistically tested until all of the engineering work has been completed and the storage is gas filled.

In general, the integrity of most geological formations is questionable, which therefore rules out most potential candidates. Exceptions could be salt caverns whose conversion into hydrogen storages seems feasible, in the long term at least.

6.1 Description of Technology

Because an existing mine is to be used, there is no way to influence the basic design of the mine body and the shafts any more. This makes it even more important to take great care in selecting a suitable mine for conversion into a gas storage. The following aspects must be taken into consideration during the selection process:

- Long term stable galleries and chambers are precondition for the utilisation of the mine.
- The tunnelling and excavation method utilised should have caused as little damage as possible to the remaining rock mass. Suitable methods are room and pillar excavation and circular room and pillar excavation. Long wall mining and other mining methods which cause fracturing of the rock formation are less suitable.
- The use of milling, scraping or drilling tools is preferred for the drifting method to the use of drilling and blasting.
- Sealing the access drifts and shafts is expensive and every additional seal which has to be put into place increases the risk of an eventual leak. The smaller the number of access drifts and shafts the better.
- Damage caused during the operational period of the mine which led to the creation of migration paths or enlarged fractures within the rock mass may no longer be repairable.
- The documentation on the drifting of the mine should be as comprehensive and as credible as possible.
- The mine must have a high watertable if the storage space is to be sealed by groundwater management.
- The mine must not exceed into adjoining rock formation which might have different rock mechanical properties or permeability.

Because access to the storage is no longer possible after commissioning, supporting and reinforcing elements can no longer be evaluated or replaced once operations have begun. Rock bolting and reinforcing can be anchored in the rock mass if the strength of the host rock is considered to be inadequate in some areas. Shotcrete can be sprayed onto the wall to stabilise unconsolidated rock, and cement can also be injected into the walls by grouting.

Underground workings or zones with high water inflows must be stabilised using suitable measures or sealed off by grouting if necessary.

During the **conversion** of the mine to a gas storage the **seal of the production shafts** and underground workings have to be installed using the same methods as described in the Rock Caverns Chapter, see Section 5.1. - Pipes can be laid through the sealing structure for the gas operation [2], although this is technically complicated and may represent another risk to the integrity of the structure. Alternatively, conventional wells can be drilled, cemented in the rock, and equipped with a gas production completion, including a subsurface safety valve, as already described in the Salt Caverns Section 2.1 [26], [3].

As already discussed with respect to rock caverns, the host rock itself is usually inadequately gas tight and therefore needs to be sealed off by using one or more of a range of methods. These methods are listed in Figure 5-1 and can be subdivided depending on whether they use groundwater to implement the seal or whether they use or strengthen the permeability – such as by the installation of a lining.

Sealing the storage wall can be undertaken using the same methods as discussed in the Rock Caverns Chapter and reference is therefore made to Section 5.1. However, the use of a lining in a mine which was not specifically constructed for gas storage operations is excluded here because of the complex geometry of galleries and chambers.

No test methods are known which can be used to test the integrity of unlined rock storages. Unlike salt caverns or depleted oil & gas fields, it is not possible per se to assume the integrity of the host rock or the surrounding geology. A test therefore would needs to encompass the whole test volume. Furthermore, the integrity test also has to be carried out with a test gas with a comparable viscosity, like e.g. air or Nitrogen. Obviously this requires efforts of month or years when large mines are supposed to be tested with similar accuracy than common for salt caverns.

When the mine is being filled for the first time, the air present after completion must somehow be replaced by the storage gas. To prevent the formation of a flammable or explosive mixture, the cavity can be flushed first with an inert gas to displace the oxygen before filling with hydrogen for the first time. Flushing is carried out under minimum pressure to use the smallest possible amount of gas. An alternative is be to flood the storage with water, which is then displaced by the hydrogen during gas first fill operations. However, flushing with water is not feasible in salt mines, due to leaching of the salt pillars. Additionally de-watering might be unfeasible for most mines, since they exhibit complex structures (e.g. galleries and chambers in different depths).

Operating procedure

The maximum pressure change rate must be complied with during gas first fill and later operation to also prevent the temperature from changing too much. The initial formation temperature is relatively low at shallow depth compared too much deeper lying salt caverns or pore storages. When implementing the water curtain method the water continuously circulating through the cavern will cool down the storage. This means that temperatures below 0 °C are certainly possible during longer or intense withdrawal periods. Cavities which are sealed off by water are also likely to give rise to higher water saturations in the hydrogen, which means that temperatures below 0 °C should be avoided to prevent the formation of ice. Moreover, the expansion in volume of the water which freezes in the cavern wall can enlarge fractures within the wall of the cavern. Temperature fluctuations of this kind must therefore be avoided at all costs.

It is possible for the hydrogen to be contaminated by biochemical reactions depending on the geology. A surface gas treatment plant is therefore needed in such cases to maintain the required high purity of the gas.

The high flow rate of the water in such storages can also give rise to high humidity levels in the stored gas which in turn requires the installation of a dehydration plant on the surface.

A supporting pressure or cushion gas pressure is required to maintain the mine stability, as well as to avoid the inflow of excessive volumes of water if the water curtain technology is used.

The storage is operated in pressure slide mode between the maximum and the minimum pressure. This therefore subjects the host rock to cyclic stresses even though, other than rock caverns, the mines are not designed considering these kinds of cyclic loads. The low elasticity of the crystalline rock mass can cause the development of fractures in the cavern wall under these cyclic loads, and such fractures can grow under these circumstances. This can be prevented by limiting the pressure change rate.

The stresses within the sealing structure and its integrity can be monitored by sensors. In all types of cavern storages, additional sensors can be installed to monitor the integrity of the storage, the pressure and temperature of the storage medium, and the stress state of the host rock.

Coal mines are also able to store gas. However, additionally to the volume of gas stored in the actual storage cavity, a large volume of additional gas can also be stored in the coal itself by sorption. Experience from such natural gas storages has revealed that the storage inventory can be increased by a factor of around ten as a result of this sorption process. Given the smaller molecular size of hydrogen, it can also be assumed that very significant volumes of hydrogen will be held in the coal itself.

As a consequence, it is not possible in such cases to calculate precisely the amount of gas possible to be stored in the mine. It also means that it is no longer possible to determine precisely where the stored gas is actually located and whether the storage is tight. In addition, coal constantly produces methane, and potentially other mine gases, depending on the storage pressure, and these gases will mix with the stored hydrogen. Depending on the host rock or the minerals incorporated within the rock, it is also possible for the hydrogen to become involved in chemical or biological reactions and thus to become contaminated. The influence of reactions of this kind can, however, be quantified by laboratory tests before converting an abandoned mine into a gas storage.

6.2 Experience

The first storage of **liquid hydrocarbons** in abandoned mines took place in Sweden in 1947 - 1950, and although discussed subsequently for a number of different mines, has rarely actually been implemented since [21].

The **Weeks Island** salt mine in Louisiana, USA which produced salt from 1902 to 1977 until mining continued in a neighbouring mine, was re-used as a crude oil storage. Small water inflows reported during the mining period have been stopped by grouting. The mine was converted into a strategic oil reserve and commissioned in 1981 with an oil storage volume of 14.2 Mio m³. However, the development of a fracture which penetrated the salt formation and gave rise to a sink-hole, meant that the crude oil was pumped out in 1994 by displacing it with brine. The mine was then closed and abandoned [4].

An abandoned iron ore mine in **May-sur-Orne**, in France was converted in the 1970s for the storage of **diesel** but the operation was shut down again in the 1990s.

In addition to the storage of oil and natural gas, mines can also be used to store pressurized gases. The planned conversion of the **Norton Mine in Ohio**, USA, to a compressed air energy storage is a project of this kind which has been discussed for a long time. The limestone mine was mined from 1943 to 1976 to supply raw materials for glass production. The mine was excavated using the room and pillar method. First Energy bought the mine in 1999 for $ 35 Mio They planned to convert the mine within the following 2-3 years. However, the conversion into a storage has not been realised to date [37].

The only high pressure **natural gas** storage in an abandoned mine built to date in Europe was realised in 1970 in the former GDR in the **Burggraf-Bernsdorf** potash mine. Two production shafts at the mine were sunk in 1911 to 1913 to a depth of 595.5 m and 599 m. Drifting was done with drilling machines and was suspended in 1921. The mine was then used during the Second World War as an army storage depot. It was converted into a gas storage between 1967 and 1970 and operated in respiration mode with town gas with an initial pressure range of 10 to 25 bar. Respiration means that raising and lowering the pressure is done without a compressor, merely by opening or closing the access valve to the connected high pressure supply pipeline and another pipeline operated at lower pressure. Since the pressure in the supply pipeline was increased later, and the storage had been used successfully for four years, the maximum pressure was increased to 36 bar. No gas treatment is installed since analysis of the produced gas revealed no contamination [2]. No problems or incidents concerning the storage of town gas occurred during the operating period. The Bernsdorf storage was converted from town gas to natural gas in 1993/1994. This conversion also involved modernisation of the shaft system and the surface facilities [2], [1]. This upgrading means that a theoretical operating pressure of maximum 50 bar can now be maintained. However, because no compressor is used, the maximum pressure reported is 36 bar, see Table 6-1. An economic analysis in 1984 came to the conclusion that future projects should have a geometrical storage volume of at least one million m³ and less than three shafts requiring sealing [Arnold Freiberg, 1984]. No information on the construction costs was published.

The storage of **natural gas** in **abandoned coal mines** is a special case. Two known storages of this kind have been constructed in Belgium, and one in the USA. The **Leyden** coal mine near Denver, Colorado/USA was mined between 1903 and 1950 in sub-bituminous coal in the Upper Cretaceous Laramie Formation. Around 6 million tonnes of coal were produced from two levels: the 240 and the 260 m level. The coal mine was excavated using the room and pillar method. The suitability of storing gas in the mine was investigated several years after the mine was abandoned. When the mine was abandoned, it was flooded naturally with groundwater as far as the production shafts. Videos recorded in the gas production wells drilled later showed that large parts of the mine were covered with broken rock as a result of caving in. It was therefore assumed that most of the former mined large underground cavities were filled with rocks and gravel.

The local water table was lowered, the shafts cleared and partially extended to construct a sealing structure in the three production shafts and one ventilation shaft. The plugs consisting of several layers of cement, ballast, clay and sand was continuously topped up with highly viscous drilling mud which was changed weekly. The sealing structures are located in a shale horizon. The gas operations involved the drilling of 22 production wells located to enable them to penetrate the largest of the former underground cavities.

After phased commissioning, the storage was operated with a reported working gas volume of 62 million m³ (inventory 85 million m³) between 1961 and 1988. A gas volume of several times the working gas is stored in the coal seams by sorption and could therefore no longer be precisely quantified. Gas measurements were carried out on the surface beginning in 2000 after questions were raised about the integrity of the storage. After confirming the presence of natural gas on the surface, work began in 2001 to shut down and flood the mine, and this work was completed in 2005 with the removal of all of the surface equipment.

Two natural gas storages in coal mines were realised in Belgium in the **Peronnes** and the **Anderlus** mine. After abandoning mining, both mines produced large amount of methane which was pumped into a gas pipeline. Natural gas storage operations were undertaken between 1980 and 2000 in the Peronnes mine and between 1980 and 1996 in the Anderlus mine. The gas produced from the mine had to be mixed together with propane before entering the pipeline to satisfy the gas transport specifications because the long chain hydrocarbons are absorbed by the coal and no longer produced. The two storages were shut down because of the high costs needed to seal the shafts amongst other things, which made the storage unprofitable. One of the reasons for the high costs was the intended revision on the large number of shafts, because Anderlus had 10 shafts and Peronnes had 19 shafts.

No abandoned mines have been used so far for the storage of pure **hydrogen**.

Additional information about the storages that are listed in Table 6-1 is provided in Appendix A.

Table 6-1: Existing abandoned mine storages

	Bernsdorf (Germany)	**Norton Ohio (U.S.)**	**Leyden (U.S.)**
Geology	Potash	Limestone	bituminous coal
Operator	VNG	First Energy	Public Service Company of Colorado
Stored fluid	NG	Air	NG
Seal/Lining	Rock Salt	Limestone	water management
Commission/ operation	1970	-	1961 - 1998
Volume [m³]	40,000	10,990,00	5,100,000
Reference depth [m]	600	670	225
Pressure range [bar]	12,4 – 36	55 – 110	? - 17.2
Possible working gas capacity H_2 Mio [kg]	0.40	43.89	-

6.3 Geological Formations, their Occurrence and Potential

Underground mines in Europe are mainly operated for the extraction of salt, coal and ore as well as for gypsum and limestone (chalk). All of these types of deposits occur in different geological settings which are generally related to sedimentary basins. The suitability of converting abandoned underground mines into gas storages very much depends on the individual geological and tectonic setting of the mined deposit and its caprock.

The feasibility of the underground storage of hydrogen in abandoned mines largely depends on the overall tightness of the cavity. This tightness can be provided by the tightness of the surrounding rock which e.g. can be the case in rock salt or potash mines, since rock salt has very low permeability and inherent integrity, which makes a leakage through the host rock very unlikely.

Coal has none of these properties and is only suitable as a storage host rock if it is saturated with water or completely enclosed by gas-tight rock formations. It is also very difficult to verify the gas integrity by testing because of the sorption of gases in the coal and the possible production of methane and other mine gases.

Furthermore tightness can be achieved by the presence of thick mudstone or claystone formations surrounding an ore or coal deposit. In the case of a bedded geological setting with low tectonic strain or deformation, formation tightness is maintained due to the absence of large-scale joints and fractures. However, most abandoned mines would be inappropriate both for geological and technical reasons because the caprock is not sufficiently gas tight and leakage to overlying strata can occur [6].

6.4 Feasibility

The storages existing in abandoned mines and discussed earlier are special cases from which the following general considerations are derived.

6.4.1 Health, Safety and Environment

If abandoned mines are to be sealed by groundwater management or water curtains, this is undertaken on the basis of significant water flow within the rock which in turn is used to prevent the escape of the stored medium. This process is dependent on the material properties and in particular on the viscosity of the storage medium. Because of the very low viscosity of hydrogen it is generally considered to have unfavourable properties for the implementation of these methods. Moreover, faulty engineering or blockage over long operating periods could cause some parts of the storage wall to become leaky which can be compensated for to a certain degree by raising the pressure in the remaining wells. However, the integrity is no longer maintained if the water management fails completely (water shortage or power cut).

In these scenarios, safe emptying of the storage over a short period of time is required because it is likely that the storage medium will otherwise escape to the surface. A hydrogen leak can therefore never be completely excluded. A leak could also take place along the existing shafts or along horizons or faults permeable to gas – in which case the gas could possibly escape to the surface a long distance away from the gas storage itself. This influence can be reduced by drilling a number of observation wells. Nevertheless, the construction of a storage of this kind also needs to take into consideration adequate safety distances to surrounding buildings etc.

An abandoned mine is sealed off by the sealing structure. Total failure of such a structure is unlikely because of its location within the rock mass. However, if this will take place, the large diameter of the shafts would lead to a huge outflow of hydrogen into the surrounding area. Furthermore, small leaks into the sealing structure cannot be completely excluded.

Finding locations which benefit from a second sealing formation above the storage can increase the safety factor. However, proper evidence is required to ensure that any escaping hydrogen cannot migrate along transmissive horizons and faults into possibly inhabited areas or regions used for other purposes.

The water table around a cavern is influenced by the operation of a water curtain as well as when using the natural groundwater. This can have an impact on the surrounding water table.

Generally, the re-use of an abandoned mine usually has a smaller impact on the environment and resources than the other storage options discussed in this study.

6.4.2 Required R&D

Because only a few abandoned mines have been used to date for the storage of gases under high pressure, and none of these caverns are used for storing hydrogen, it is not possible to fully assess the amount of research and development work still required.

In all of the storage options considered here, materials must be identified for the sealing structure, as well as for the production wells, which are resistant to hydrogen corrosion, and sufficiently tight.

Only very few gas storages have been constructed in **limestone** (e.g. Gargenville, see Chapter 5.2) [20]. The permeability of lime stone varies in a broad range and only few occurrences may be utilised to store high pressure gases. Therefore specific exploration and testing is required to get information about the suitability of formations.

The integrity of salt with respect to gas has already been proven by the successful operation over many years of salt cavern storages for natural gas and hydrogen. In addition, laboratory permeability tests are currently being carried out with hydrogen as the test gas.

The use of **water curtain** technology to **seal coal** to enable the storage of hydrogen has so far not been documented in the literature. Because of the high mobility of hydrogen, tests need to be carried out to determine the maximum pressure differences that can be operated in such storages without jeopardising their technical integrity.

Depending on the host rock, chemical or biological reactions could take place which could contaminate the stored hydrogen. The reactivities of the geological formations at a specific location, can, however, be investigated on site.

New methods may have to be developed to verify the gas tightness of gas storages, and this may entail testing the integrity of the underground workings step-by-step.

6.4.3 Costs

The costs for using abandoned mines for the storage of hydrogen or other gases stored under high pressure are largely dependent on the specific mine being considered. Moreover, no information was provided on the costs in the projects referred to in Section 6.2 (Experience).

The costs are already generated early during the acquisition phase of the mine and construction of the sealing structure. This means that comprehensive investigations are required on the geology, and as far as possible, tests should also be carried out on the integrity of each zone or the whole storage to enable the risk to be estimated. However, complex sealing structures are necessary to carry out in situ integrity tests, and under certain circumstances, may nevertheless not be able to be used to carry out a test at the intended storage pressure.

If the geology only has limited tightness to gas, it may be necessary to set up a monitoring system with observation wells and gas monitoring on the surface.

Nevertheless, the lower costs associated with re-using an existing mine will probably compensate for the aforementioned costs.

6.4.4 Risks

Because of the very inhomogeneous spectrum of storage options, it is hardly possible to specify any general risks which may highlight that abandoned mines are generally unsuitable for the storage of hydrogen.

In the case of abandoned coal mines, the difficulty of carrying out tightness tests to confirm the integrity (due to sorption of the gas in the coal seams) is certainly a serious deficit. Moreover, the long-term integrity of storages sealed by groundwater or water curtains is questionable, especially if problems occur during operations. Nevertheless, if salt mines are used, the integrity of the host rock can generally be assumed because of the well-established specific material properties of rock salt.

Integrity tests of the storage cavity before purchasing a mine, or before and after major conversion work has been done, would also be desirable to reduce the financial risk. However, such tests are only possible to a very limited extent or not possible at all because of the large cross-sections involved and the high storage pressures. Verifying the integrity and with this the overall suitability of the gas storage can therefore only be undertaken once all of the construction work has been completed.

General risks associated with this storage option are linked to the sealing structures needed to plug the shafts. If these structures are designed and built professionally, they should be able to guarantee the permanent mechanical sealing of the storage. Another risk is the potential of small leaks developing along the contact surfaces of the sealing structure. Monitoring can continuously check the stability and integrity of the sealing structure.

Small tectonic events (tremors) can be generated as a consequence of the construction of the caverns or mines. These tectonic events can only be damped to a very limited degree by stiff rock formations. This could lead to damage to the storage structure. Such tectonic movements could also have a negative impact on the groundwater management and therefore the overall sealing system protecting the storage [6].

6.5 Performance / Characteristic of Storage Option

Most of the discussed abandoned conventional mines provide very large geometric volumes. However, they cannot be altered to match the required (e.g. smaller) dimensions.

They also provide low flexibility since the mine workings are not designed for dynamic pressure rates but for static loads at ambient pressure. Additionally, the groundwater management or the water curtain technique reduces the feasible pressure rates and their bandwidth. The mines therefore require large cushion gas volumes and could probably perform best as seasonal storages.

Therefore the mentioned issues are also the reasons why a prediction of possible hydrogen rates for these kinds of storages is not done in this study.

The gas withdrawn from abandoned conventional mines will probably have a high water content due to groundwater management or even the application of the water curtain technique. Depending on the present host rock also a degradation of hydrogen might occur which potentially leads to a loss of hydrogen and impurities from the products of biological or chemical reactions. Impurities of the produced hydrogen might also occur if mine gas is entering the storage.

As mentioned above the different types of abandoned mines vary a lot and only few storages of this kind have been realised yet. Therefore, no quantitative data about feasible storage volumes and rates can be provided within this study.

7 Pipe storage

Pipe storages are not generally classified as geological storages because they are only buried a few metres below ground level. They are therefore also independent of the local geology. In terms of materials and the means of construction, they correspond to conventional pipes used in pipelines, but are laid out parallel to one another and joined up.

Pipe storages are used to store natural gas and smooth out short-term demand peaks, e.g. at larger facilities or cities with limited connectivity to the gas grid. The pipe storage built so far are not big enough to make any significant contribution to seasonal storage requirements.

The construction costs comprise mainly on the procurement costs for the steel pipes and the welding, as well as the earth moving work. The surface facilities largely are comprised of a compressor and the gas metering system because no gas treatment is required.

Because hydrogen pipelines already exist (amongst others in Germany) and pipe storages have no significant differences to these pipelines, it is considered that storing hydrogen in pipe storages is a soon achievable option.

7.1 Description of Technology

Design considerations

The storage is sealed by the steel pipes utilised and is therefore completely independent of the local geology or soil type in which the pipes are laid. The stability and the pressure range under which the storage can be operated are purely determined by the strength and thickness of the pipes.

Unlike the before described underground geological storages the balancing between increasing the storage pressure by greater storage depth and decreasing the investment costs for drifting or drilling shorter shafts or wells is not an issue for pipe storages. Moreover, for the storage types considered so far, a large proportion of the construction costs are accounted for by constructing the access to the storage. This is added to a share of the costs which is more or less proportional to the size of the storage. In the case of pipe storages, the proportion of fixed costs is very small because it is only related to the surface facilities. This leads to a lower economic necessity to build large storages, which is common for all the other storage options to achieve a low quotient of CAPEX per working gas volume.

Depending on how the storage is connected to the natural gas grid, the pipeline pressure could either define the minimum storage pressure or the gas could be produced from the storage at reduced pressure via a compressor.

The storage pipes are buried deep enough in the ground to enable the surface to be used, although this is subject to significant restrictions, but can include agricultural activities for instance. The land must therefore be purchased for storage construction or acquired in some other way.

Construction

The construction of a pipe storage mainly involves on site civil construction works and welding activity. After excavating a suitable hole to accommodate the storage pipes, the storage pipes are laid on a bed of sand or ballast. The individual pipes with diameters of up to 1.4 m are welded together on site to form a storage pipe with a total length of up to several hundred metres. Their ends are sealed with hemispherical ends. These pipes strings are connected to one another via connection pipes. The connecting pipes with their smaller diameters are also the expansion components and help disperse the high stresses which can occur, for instance due to the temperature changes which arise during injection and production.

Coatings are applied to the storage pipes and connecting pipes to protect them against corrosion, and additional corrosion protection measures can also be installed by using cathodic corrosion protection.

The horizontal alignment of the storage pipes with a defined gradient (approx. 0.5 %) allows any forming condensate to collect at the lowest point in the pipes where it can be removed via valves. Venting valves are positioned at the highest point to enable the tightness and pressure test of the pipes. This test takes place after the storage has been constructed (and in accordance with the pressure vessel regulations) by pumping water into the storage until it has reached the test pressure. During gas first fill, this water can either be directly displaced by the storage medium or the storage can be drained and then dried with air first. In this case, the storage would also be flushed out with nitrogen before gas first fill to prevent the formation of a flammable hydrogen/air mixture. Although flushing with nitrogen appears to be more expensive, it also enables the storage to be dried and therefore reduces the water saturation of the stored medium.

When all of the work has been completed (including testing the tightness) the excavation holding the storage pipes is filled with soil again. The renaturised surface could then be used for agricultural purposes or other use. The erection of building on top of the storage is not considered prudent.

Publications report that construction of a storage with a length of more than 200 m and a geometrical volume of 6,112 m^3 would require a pure construction period of eight months. Because of the large area involved and the good accessibility of the construction site, it is possible for construction work to be carried out in parallel, which can speed up the construction phase if required.

Operating procedure

In a similar way to geological storages, the operation of a pipe storage involves maintaining a minimum pressure. This has nothing to do with the stability of the storage, but rather with the pressure difference between the storage and the pipeline and the associated need to keep the compressor work reasonable.

If large pressure rates occur during injection or withdrawal, this will change the temperature of the gas and the steel pipes and affect the length of the storage by thermal expansion. Depending on the intended pressure range, it may be necessary to limit the length of the pipes or to enable the pipes to expand without damaging or hindering the operation. This can be achieved by creating special floating bearings and installing expansion spaces at the end of the storage pipes [16].

No contamination or increase in the humidity of the gas in the storage is expected during standard operations. This means that no drying or purification equipment is required.

7.2 Experience

Natural gas pipe storages have widely been used since the 1980s primarily by municipal utilities for peak shaving on a weekly or daily basis. Some of these storages have been operating successfully for many decades.

A literature search only revealed storage projects in Germany, Austria and Switzerland. It is not clear whether the technology has been used in other European countries either or has just not been documented. Some of these projects are described in [22].

The construction of several gas storage projects for long-term supply and demand balancing has been discussed in Switzerland in recent years. Because of the Swiss geology, the focus was mainly on the construction of lined rock caverns. However, some pipe storages were also constructed for peak shaving. One of these storages was built in 8 months by Erdgas Zürich Transport AG and commissioned in 2013. The storage consists of 20 pipe strings each consisting of 13 pipe sections with a diameter of 1.4 m. These produce a geometrical volume of 6,112 m³ and enable a working gas volume of Mio 0.5 m³(st) hydrogen to be stored. The CAPEX for the natural gas storage was around € 17 Mio, see Table 7-1 [34].

There are no known pipe storages for storing **hydrogen**. However, hydrogen pipelines exist especially in chemical and petro industries.

Additional information about the storages listed in Table 7-1 is provided in Appendix A.

Figure 7-1: Photography of pipe storage construction workings for the Zürich Transport AG [40]

Table 7-1: Existing Pipe Storages

	Urdorf near Zürich (Switzerland)	**Bocholt, [17] (Germany)**	**Bern Eymatt (Switzerland)**	**Wien, [39] Leopoldau (Austria)**
Geology	-	-	-	-
Operator	Erdgas Zürich Transport	Bocholter Energie- und Wasser-versorgung	GVM – Gasverbund Mittelland	Wien Energie Speicher
Stored fluid	Natural gas	Natural gas	Natural gas	Natural gas
Commission/ operation	2012	2007	2007	2011
Volume [m³]	6,112	3,072	7,955	12,400
Reference depth [m]	-	-	-	-
Pressure range [bar]	7 - 100	- 90	23 - 70	4 ~ 45
Possible working gas capacity H_2 Mio [kg]	0.045	0.021	0.030	0.042

7.3 Geological Formations, their Occurrence and Potential

No special geological formation is required for the construction of pipe storages. However, a certain thickness of soil is required.

7.4 Feasibility

A large number of pipe storages have already been constructed in Germany and neighbouring countries. There are also existing high pressure hydrogen pipelines which link the producers and consumers of hydrogen in the chemical industry. Because pipe storages are constructed in exactly the same way as these pipelines, it is already feasible to construct pipe storages for hydrogen today.

7.4.1 Health, Safety and Environment

Constructing the storage initially requires conventional earth moving activities as well as standard pressurised vessel construction or pipeline construction. There are therefore no special hazards associated with this work.

Because the storage pipes are buried at a shallow depth, the pipes could potentially be damaged by surface events. The areas above the storage can therefore only be used in a restricted way. If one of the storage pipes is damaged, hydrogen will immediately escape to the surface where it could ignite. The gas in the neighbouring pipes strings will then also flow out but at a much lower rate, because of the reduced diameter of the connector pipes. The installation of safety valves between the storage pipes strings could prevent the escape of gas from the other strings in this scenario. The aforementioned risk means that the pipe storage should be located at an appropriately safe distance from surrounding buildings and settlements.

Inspecting the pipes for corrosion would require the storage pipes to be uncovered. Using the pigs (pipeline inspection gauge) conventionally utilised in pipeline construction and operation is not possible in this case, due to the missing entry and exit points.

The usual environmental impacts associated with civil construction work and material transport also affect the construction of a pipe storage. Low environmental impact is expected during the operations phase. The impact on the surroundings is also relatively minor because the surface can be renaturised after construction of the storage.

7.4.2 Required R&D

One of the main aspects, as already discussed with all of the storage options, is to test the compatibility of the steel with the hydrogen to be stored in the pipes. Because hydrogen pipelines are already used in Germany and other countries, it can be assumed that almost no additional research and development work will be required.

7.4.3 Costs

As mentioned earlier, the storage costs increase fairly proportionally to the storage volume because less preparatory work such as sinking shafts or drilling boreholes is required to create the access to the storage. The additional investment costs for the gas compressor and the metering and control section including the possible use of a heat exchanger are all dependent on the planned gas throughput.

Experience from pipeline engineering reveals that the largest share of the construction costs will be the material costs for the storage pipes, even though the pipes are produced in large numbers for pipelines. The costs for welding and civil engineering are a factor of three to four times lower. The costs for excavation and welding are strongly dependent on the wage levels in the relevant country or region. Another cost factor is the cost of land and these could be considerable given the large amount of land required.

7.4.4 Risks

Because of the similarities between gas pipeline construction and the construction and operation of a pipe storage, the erection of such a storage could proceed in compliance with the country specific high pressure gas pipeline regulations. Moreover, hydrogen pipelines are already operated in several countries which means that only minimal approval risks are to be expected. Nevertheless, there could be risks linked to the public acceptance of a shallow hydrogen storage.

7.5 Performance / Characteristics of the Storage Options

The storage capacity of pipe storages is very small compared to other investigated storage options. A maximum geometric volume of roughly 12,000 m^3 has been realised so far. Since the storage pipes are easily accessible, they and can be extended by additional pipes after commissioning of the storage. Due to very small minimum pressures which can reach values of only 4 bar only little quantities of cushion gas is required. Working gas capacities of 42,000 kg hydrogen are feasible with only 4,200 kg cushion gas. Pipe storages provide a high flexibility and may reach injection and withdrawal rates of up to 90,000 m^3(st)/h for natural gas which is in the same range as for salt caverns. Hydrogen rates of 7,400 kg/h appear to be feasible if the same pressure rate is.

With the given withdrawal rate the whole working gas may be withdrawn in just six hours. Therefore, storage pipes are commonly applied for peak shaving on a weekly or daily basis. As a matter of fact, they may have a very high number of turnovers per year, which helps to distribute the high specific construction costs to a large gas volume that might be stored in the pipes during the storages lifetime. However, pipe storages remain the most expensive storage option investigated in this report, related to the CAPEX per working gas.

Another advantage is that no humidity or other impurities will accumulate in the stored hydrogen, since the gas is encapsulate by a technically designed surface.

HyUnder, Deliverable 3.1: Overview on all known Underground Storage Technologies for Hydrogen
Appendix A: Detailed information about selected storage as examples for the investigated storage options

	Salt Caverns				Aquifers		Depleted Gas Fields		Rock Caverns				Abandoned Mines			Pipe Storage			
	Green field design (-)	Clemens (USA)	Moss Bluff (USA)	Teeside (USA)	Hähnlein (GER)	Stenlille (DEN)	Uelsen (GER)	Rheden (GER)	Haje (CZE)	Sandia Study (-)	Skallen (SWE)	Sofregaz Study (-)	Bernsdorf (GER)	Leyden (USA)	Norton Ohio Project (USA)	Urdorf, Zürich (SUI)	Bocholt (GER)	Bern Eymatt (SUI)	Leopoldau (AUT)
Storage parameter																			
Geology	Rock salt	Rock salt	Rock salt	Rock salt	Detfurth Standstone	Sandstone	Detfurth Sandstone	Zechstein/ Dolomite	Granite	Granite	Gneiss	-	Carnalit	Bituminous Coal	Limestone	-	-	-	-
Operator	-	Conoco-Phillips	Praxair	Sabic Petro	E.On	DONG	Storengy	ASTORA	RWE Transgas	-	E.On Sverige	-	VNG	-	First Energy	Erdgas Zürich Transport	BEW Bocholt	GVM	Wien Energie Speicher
Stored product	Hydrogen	Hydrogen	Hydrogen	Hydrogen	Natural Gas	Natural Gas	Natural Gas	Natural Gas	Natural Gas	Air	Natural Gas	Natural Gas	Natural Gas	Natural Gas	Air	Natural Gas	Natural Gas	Natural Gas	Natural Gas
Seal / Lining	Rock salt	Rock salt	Rock salt	Rock salt	Claystone	Cap rock	Cap rock	Cap rock	Insitu	Water Curtain	Steel lining	Steel lining	Rock salt	Groundwater	Insitu	Steel	Steel	Steel	Steel
Commission / Operation		1983	2007	~1972	1960	1989	1997	1993	1998	-	2004	-	1970	1961 - 1998	-	2012	2007	2007	2011
Reference depth [m]	1000	930	>822	380 - 380	500	1500	1500	1900 - 2100	950	114	600	-	600	225	670	-	-	-	-
Geometrical volume [m³]	500.000	580.000	566.000	210.000	(3.198.282)	(4.141.615)		(32.797.585)	620.000	1.010.900	40.000	320.000	135.000	5.100.000	10.990.000	6.112	3.072	7.955	12.400
Maximum pressure [bar]	180	135	152	46	53	170	165	280	125	60	230	230	50	17,2	110	100	90	70	45
Minimum pressure [bar]	60	70	55		39	150		110	*38*	30	10	38	12,4	6,895	55	7	4	23	4
Storage Capacities																			
Natural Gas (NG)																			
Cushion gas [Mio. kg]	24,9	34,3	25,5	0,0	69,3	562,7	-	2.424	18,8	25,4	0,3	10,8	1,34	28,4	534	0,04	0,01	0,16	0,04
Working gas [Mio. kg]	59,4	38,5	55,2	8,5	69,3	303,0	649,3	3.636	53,7	29,8	9,5	66,0	4,64	44,6	680	0,65	0,29	0,41	0,48
Cushion gas [Mio. m³(st)]	30,3	41,9	31,1	0,0	84,4	686,1		2.955	23,0	31,0	0,4	13,1	1,63	34,7	651	0,04	0,01	0,19	0,05
Working gas [Mio. m³(st)]	72,4	46,9	67,3	10,3	84,4	369,4	791,6	4.433	65,5	36,4	11,5	80,5	5,66	54,4	829	0,79	0,35	0,50	0,58
Cushion gas [GWh] [1]	366	506	376	0	1.020	8.284	-	35.685	277	374	5	159	19,7	418	7.863	0,5	0,1	2,3	0,6
Working gas [GWh] [1]	875	566	812	125	1.020	4.461	9.559	53.528	791	439	139	972	68,4	656	10.013	9,5	4,3	6,0	7,0
Costs of cushion gas [Mio. €] [1,2]	9,5	13,1	9,8	0,0	25,5	207,1		892,1	6,93	9,36	0,12	3,97	0,493	10,46	197	0,013	0,004	0,058	0,015
Hydrogen (H_2)																			
Cushion gas [Mio. kg]	2,21	2,98	2,30	0,00	6,27	35,37		208,6	1,77	2,41	0,03	0,98	0,134	2,90	46,8	0,004	0,001	0,015	0,004
Working gas [Mio. kg]	4,00	2,56	3,72	0,76	6,27	19,04		312,8	3,78	2,32	0,64	4,34	0,395	4,28	43,9	0,045	0,021	0,030	0,042
Cushion gas [Mio. m³(st)]	26,0	34,9	27,0	0,0	73,6	415,3		2.449	20,8	28,3	0,4	11,6	1,58	34,0	550	0,04	0,01	0,18	0,05
Working gas [Mio. m³(st)]	46,9	30,1	43,7	8,9	73,6	223,6		3.674	44,3	27,3	7,5	50,9	4,64	50,3	515	0,53	0,25	0,35	0,49
Cushion gas [GWh] [1]	87,1	117,2	90,6	0,0	247,0	1.393,1		8.215	69,7	94,8	1,3	38,7	5,29	114,1	1.844	0,14	0,04	0,60	0,16
Working gas [GWh] [1]	157,4	100,8	146,7	29,9	247,0	750,1		12.322	148,7	91,6	25,1	170,8	15,58	168,7	1.729	1,77	0,83	1,17	1,64
Costs for cushion gas [Mio. €] [1,3]	4,977	6,698	5,179	0,000	14,115	79,606	0,000	469,419	3,985	5,419	0,075	2,214	0,302	6,517	105,373	0,008	0,002	0,034	0,009
Production and Injection rates																			
Natural Gas																			
Injection [kg/h]	104.000				69.000	296.000	216.000	1.212.000	216.000		13.000	133.000	35.000	35.000					
Withdrawal [kg/h]	104.000				87.000	173.000	390.000	2.078.000	325.000		35.000	267.000	35.000	35.000					74.000
Hydrogen																			
Injection [kg/h]	10.800				7.200	30.700	22.500	125.800	22.500		1.300	13.900	3.600	3.600					
Withdrawal [kg/h]	10.800				9.000	18.000	40.400	215.700	33.700		3.600	27.700	3.600	3.600					7.600
CAPEX [4]																			
CAPEX for storage [Mio. €]	28,1							375,0	92	318	27	173				16,9		8,5	
CAPEX per geom. volume [€/m³]	56,1							11,4	148	315	675	541				2.763		1.069	
Natural Gas																			
CAPEX per working gas [€/kg]	0,47							0,10	1,71	10,67	2,85	2,62				26,1		20,9	
CAPEX per working gas [€/m³(st)]	0,39							0,08	1,40	8,75	2,34	2,15				21,4		17,1	
CAPEX per working gas [€/GWh] [1]	**30,4**							**6,64**	**110**	**687**	**184**	**169**				**1.683**		**1.345**	
Hydrogen																			
CAPEX per working gas [€/kg]	7,02							1,20	24,4	137,0	42,3	39,9				376,4		285,7	
CAPEX per working gas [€/m³(st)]	0,60							0,10	2,07	11,66	3,60	3,40				32,1		24,3	
CAPEX per working gas [€/GWh] [1]	**168,9**							**28,8**	**586**	**3.295**	**1.017**	**960**				**9.055**		**6.871**	

1: Energy related to upper heating value (14.72 kWh/kg for natural gas, 39.39 kWh/kg for hydrogen)
2: Energy costs of 25€/MWh for natural gas, EEX/GASPOOL average prices (25.06.2013)
3: Energy costs of 40€/MWh for hydrogen electrolyses, EEX/ELIX 200 d average base prices (25.06.2013)
4: Excluding cushion gas

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Working gas [Mio. m³(st)]	72,4	46,9	67,3	10,3	84,4	369,4	791,6	4.433	65,5	36,4	11,5	80,5	5,66	54,4	829	0,79	0,35	0,50	0,58
Cushion gas [GWh] [1]	366	506	376	0	1.020	8.284	-	35.685	277	374	5	159	19,7	418	7.863	0,5	0,1	2,3	0,6
Working gas [GWh] [1]	875	566	812	125	1.020	4.461	9.559	53.528	791	439	139	972	68,4	656	10.013	9,5	4,3	6,0	7,0
Costs of cushion gas [Mio. €] [1,2]	9,5	13,1	9,8	0,0	25,5	207,1		892,1	6,93	9,36	0,12	3,97	0,493	10,46	197	0,013	0,004	0,058	0,015
Hydrogen (H_2)																			
Cushion gas [Mio. kg]	2,21	2,98	2,30	0,00	6,27	35,37		208,6	1,77	2,41	0,03	0,98	0,134	2,90	46,8	0,004	0,001	0,015	0,004
Working gas [Mio. kg]	4,00	2,56	3,72	0,76	6,27	19,04		312,8	3,78	2,32	0,64	4,34	0,395	4,28	43,9	0,045	0,021	0,030	0,042
Cushion gas [Mio. m³(st)]	26,0	34,9	27,0	0,0	73,6	415,3		2.449	20,8	28,3	0,4	11,6	1,58	34,0	550	0,04	0,01	0,18	0,05
Working gas [Mio. m³(st)]	46,9	30,1	43,7	8,9	73,6	223,6		3.674	44,3	27,3	7,5	50,9	4,64	50,3	515	0,53	0,25	0,35	0,49
Cushion gas [GWh] [1]	87,1	117,2	90,6	0,0	247,0	1.393,1		8.215	69,7	94,8	1,3	38,7	5,29	114,1	1.844	0,14	0,04	0,60	0,16
Working gas [GWh] [1]	157,4	100,8	146,7	29,9	247,0	750,1		12.322	148,7	91,6	25,1	170,8	15,58	168,7	1.729	1,77	0,83	1,17	1,64
Costs for cushion gas [Mio. €] [1,3]	4,977	6,698	5,179	0,000	14,115	79,606	0,000	469,419	3,985	5,419	0,075	2,214	0,302	6,517	105,373	0,008	0,002	0,034	0,009
Production and Injection rates																			
Natural Gas																			
Injection [kg/h]	104.000				69.000	296.000	216.000	1.212.000	216.000		13.000	133.000	35.000	35.000					
Withdrawal [kg/h]	104.000				87.000	173.000	390.000	2.078.000	325.000		35.000	267.000	35.000	35.000					74.000
Hydrogen																			
Injection [kg/h]	10.800				7.200	30.700	22.500	125.800	22.500		1.300	13.900	3.600	3.600					
Withdrawal [kg/h]	10.800				9.000	18.000	40.400	215.700	33.700		3.600	27.700	3.600	3.600					7.600
CAPEX [4]																			
CAPEX for storage [Mio. €]	28,1							375,0	92	318	27	173				16,9		8,5	
CAPEX per geom. volume [€/m³]	56,1							11,4	148	315	675	541				2.763		1.069	
Natural Gas																			
CAPEX per working gas [€/kg]	0,47							0,10	1,71	10,67	2,85	2,62				26,1		20,9	
CAPEX per working gas [€/m³(st)]	0,39							0,08	1,40	8,75	2,34	2,15				21,4		17,1	
CAPEX per working gas [€/GWh] [1]	**30,4**							**6,64**	**110**	**687**	**184**	**169**				**1.683**		**1.345**	
Hydrogen																			
CAPEX per working gas [€/kg]	7,02							1,20	24,4	137,0	42,3	39,9				376,4		285,7	
CAPEX per working gas [€/m³(st)]	0,60							0,10	2,07	11,66	3,60	3,40				32,1		24,3	
CAPEX per working gas [€/GWh] [1]	**168,9**							**28,8**	**586**	**3.295**	**1.017**	**960**				**9.055**		**6.871**	

1: Energy related to upper heating value (14.72 kWh/kg for natural gas, 39.39 kWh/kg for hydrogen)
2: Energy costs of 25€/MWh for natural gas, EEX/GASPOOL average prices (25.06.2013)
3: Energy costs of 40€/MWh for hydrogen electrolyses, EEX/ELIX 200 d average base prices (25.06.2013)
4: Excluding cushion gas