“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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Benchmarking of Selected Storage Options

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R E P O R T

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1 Introduction

The majority of natural gas storage is done in underground storages in deep geological formations because they are extremely safe, environmentally sustainable, allow large storage capacities and have low specific costs compared to surface storages. These are the reasons for the large interest in using such storages in future for storing gaseous high pressure hydrogen, too.

Work Package 3 (WP3) “Assessment of geologic options for hydrogen underground storage” investigates the suitability of all potential feasible geologic storage options for high pressure hydrogen storage. To achieve the stated objectives, WP3 has been organised as follows into five tasks and thus five deliverables:

- 3.1 - Overview on underground storage technologies
- 3.2 - Develop evaluation criteria for selection of suitable storage options
- 3.3 - **Benchmarking of selected storage options (this paper)**
- 3.4 - Detailed study of the key candidates for underground hydrogen storage
- 3.5 - Definition of model storage projects to be used for later case studies

Deliverable 3.1 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. Deliverable 3.2 documents the evaluation criteria and a weighting system that were derived to prepare the subsequent benchmarking and ranking of the storage options. The present Deliverable 3.3 documents the benchmarking and the short list representing the three best suitable storage option for high pressure hydrogen storage in Europe.

The following chapter 2 documents to what extend the criteria are fulfilled by the different storage options and the resulting rating.

In chapter 3 the results of the rating are cumulated in tabular form and in a brief summary of the benchmarking to provide the short list of the three key storage options to be further investigated in the subsequent Deliverable 3.4.

2 Benchmarking of storage options

The following benchmarking of the geologic options to store high pressure hydrogen is performed based on Deliverable 3.1, which provides the background information for each of the storage options and on Deliverable 3.2, which provides the evaluation criteria including weighting factors. For the assessment of the criteria the below five ratings were defined:

- very good + +
- good +
- fair o
- poor -
- insufficient - -

If one criterion is assessed with the rating "insufficient" the storage option is excluded independently of weighting and other ratings. Therefore rating "insufficient" is only applied if safety related criteria or other key criteria (e.g. suitable capacity to provide long term storage) are not fulfilled sufficiently.

2.1 Tightness of storage

Salt Caverns

- Combination of gas tightness of rock salt as well as large pillar width beside and thick salt layer above and below caverns provide very good tightness.
- Tightness for hydrogen is proven by laboratory tests and practical experience.
- Very good experience with natural gas and North American hydrogen caverns.

➔ very good (+ +)

Depleted Oil Fields

- Seal above porous formation provided long term tightness for hydrocarbons until start of exploitation, otherwise the hydrocarbons would have migrated to surface. However, the tightness of gases and especially hydrogen still needs to be proven.
- Geological and reservoir mechanical properties well know from exploration and oil production.
- Good experience with natural gas storage after oil depletion.
- Existing wells were not designed for hydrogen storage; need to convert or plug wells.

➔ good (+)

Depleted Gas Fields

- Seal above formation provided long term tightness for hydrocarbon until start of exploitation, otherwise gas would have migrated to the surface.
- Very good experience with natural gas storage after depletion.
- Existing wells were not designed for hydrogen storage; need to convert or plug wells.

➔ very good (+ +)

Aquifers

- Numerous aquifer formations for natural gas storage worldwide have proven general suitability of this option.
- The gas tightness of the sealing formation above the aquifer formation must be proven by comprehensive exploration effort. The tightness can be tested by packer tests in the uncased well and by laboratory tests on core samples.
- Tightness of common types of cap rock to hydrogen needs to be investigated.

➔ very good (+ +)

Lined Rock Caverns

- Good gas tightness of steel lining (material and welding).
- Suitable steel for hydrogen storage needs to be selected.
- No experience with long term tightness of cavern wall with small thickness of lining.

➔ good (+)

Unlined Rock Caverns

- Gas tightness depends on water management, which may fail under some circumstances.
- Tightness of water management storages for hydrogen still needs to be investigated.
- Under dynamic load rock mass tends to form fractures which may lead to leakages.

➔ poor (-)

Abandoned Salt Mines

- Very low permeability of rock salt itself generally provides good tightness, even for hydrogen.
- Practical experience of high pressure gas storages in caverns in rock salt.
- Mines were not designed for storage regarding tightness and rock mechanical stability at high pressure and fluctuating pressures.
- Most salt mines show some water/brine inflow, which may lead to a leakage in case of later use for high pressure gas storage.

- ○ Access to salt mines is provided by several shafts of large horizontal cross section. Sealing of these shafts for later gas storage is a difficult and costly engineering task.
- ○ Some positive experience with one salt mine for natural gas; no experience with hydrogen.

➔ fair (o)

Abandoned Limestone Mines

- ○ Lime stone is very stiff and tends to form fractures.
- ○ Low permeability of selected lime stone formations may provide tightness for common gases. However, only very few occurrences of lime stone provide suitable conditions.
- ○ No practical experience of high pressure gas storage in lime-stone formations, especially for hydrogen.
- ○ Mines were not designed for storage regarding tightness and rock mechanical stability at high pressure and fluctuating pressures.
- ○ Most mines show some water/brine inflow, which may lead to a leakage.
- ○ Complicated geometry of mines before abandonment; difficult to assess later gas tightness.
- ○ Access to mines is provided by several shafts of large cross section. Sealing of these shafts for later gas storage difficult and costly engineering task.

➔ poor (-)

Abandoned Coal Mines

- ○ Access to mines is provided by several shafts of large cross section. Sealing of these shafts for later gas storage difficult and costly task.
- ○ Poor experience with natural gas storage: Largest mine of this kind (Leyden) was closed due to gas leakage.
- ○ Complicated geometry of mines before abandonment; difficult to assess later gas tightness.
- ○ Tightness of host-rock is highly questionable, tightness is provided by water management.
- ○ Gas tightness depends on water management which can fail.
- ○ Tightness of water management storages for hydrogen needs to be investigated.

➔ **insufficient (- -)**

Pipe Storage

- ○ Very good tightness of storage pipes due to application of technical materials.
- ○ Good experience with natural gas pipe storages and hydrogen pipelines.

➔ very good (+ +)

2.2 Feasibility to prove tightness

Salt Caverns

- Practical experience with several hundred high pressure gas caverns has proven gas tightness of cavern body in homogeneous salt formations; even good experience with existing high pressure hydrogen caverns. Additionally tightness of rock salt samples is tested by laboratory tests. Thus only the well bore consisting of cemented casings needs to be tested.
- Tightness test for well bores is standard practise and can quantify the tightness of the well bore with high accuracy.

➔ very good (+ +)

Depleted Oil Fields, Depleted Gas Fields

- Tightness of sealing formation for hydrocarbons is obvious. Additionally tightness for high pressure hydrogen is tested in the well by packer tests and by laboratory testing of cap rock samples.
- If the tightness of the sealing formation is proven, only the well bores need to be tested.
- Tightness test for well bores is standard practise. However, only tightness against liquids is tested.

➔ very good (+ +)

Aquifer Storages

- Geometry (trap type and structure) and possible leakage paths (through faults or fractures) can be investigated by seismic exploration, drilling of exploration wells and well tests. However, due to the resolution of the available methods it is not possible to eliminate the existing uncertainty.
- Tightness of the formation seal (material) can be tested during exploration by packer tests in the well and by laboratory testing of core samples.
- Packer test in well bores is standard practise. However, only tightness against liquids is tested.
- Tightness of the storage needs to be monitored continuously by monitoring wells.

➔ good (+)

Lined Rock Caverns

- To proof tightness against gases the whole cavern needs to be pressure tested with high pressure gas (e.g. air or nitrogen), which requires long preparation and testing durations.
- Tightness test can be supported by measuring the temperature and pressure inside the storage.
- In case of a leak the detection of the leak location is difficult.
- In case of leakage gas can be monitored by gas sensors outside the seal.

➔ fair (o)

Unlined Rock Caverns

- To proof tightness against gases the whole cavern needs to be pressure tested with high pressure gas (e.g. air or nitrogen), which requires very long preparation and testing durations.
- Tightness test can be supported by measuring the temperature and pressure inside the storage.
- In case of a leak the detection of the leak location is very difficult.
- Tests require long test durations due to large volumes.
- Prerequisite of a tightness test is the installation of the expensive shaft plugs.
- Tightness may depend on performance of water management and tightness may therefore decrease during operation.

➔ poor (-)

Abandoned Salt Mines and Abandoned Limestone Mines

- To proof tightness against gases the whole cavity needs to be pressure tested with high pressure gas (e.g. air or nitrogen), which requires very long preparation and testing durations.
- Tightness test can be supported by measuring the temperature and pressure inside the storage.
- Tests require unreasonable long test durations due to very large volumes.
- Prerequisite of a tightness test is the installation of the expensive shaft plugs.

➔ **insufficient (- -)**

Abandoned Coal Mines

- To proof tightness against gases the whole cavity needs to be pressure tested with high pressure gas (e.g. nitrogen), which requires long preparation and testing durations.
- Tightness test can be supported by measuring the temperature and pressure inside the storage.
- Prerequisite of a tightness test is the installation of the expensive shaft plugs.
- Tightness test cannot give significant results due to the capability of coal to adsorb gases. It is therefore not possible to quantify the potential leak rate.

➔ **insufficient (- -)**

Pipe Storage

- Tightness can be tested by pressure tests with water and test gases.
- Good experience from testing of pipelines.

➔ very good (+ +)

2.3 Practical experience

Salt Caverns

- Broad positive experience with natural gas storage and positive experience with several hydrogen caverns in the USA and in the UK.
- Experiences can to a large extend be applied for hydrogen storage.

➔ very good (+ +)

Depleted Oil Fields

- Some experience with natural gas storage. However, mixing with hydrocarbon residues caused problems (reason why depleted gas fields are the preferred option for natural gas storage).
- Experience with town gas storage shows some hydrogen depletion due to chemical reactions. On example are carbon oxides to produce methane in town gas. However, in town gas a share of CO and CO_2 was injected together with hydrogen. This would not be the case for future hydrogen storage.
- No experience with the storage of pure hydrogen.

➔ fair (o)

Depleted Gas Fields, Aquifers

- Large positive experience with natural gas storage.
- Experience with town gas storage shows some hydrogen depletion due to chemical reactions. On example are carbon oxides to produce methane in town gas. However, in town gas a share of CO and CO2 was injected together with hydrogen. This would not be the case for future hydrogen storage.
- No experience with the storage of pure hydrogen.

➔ good (+)

Lined Rock Caverns

- Only a single storage for natural gas was constructed yet (pilot plant Skallen).
- No experience with hydrogen storage.

➔ fair (o)

Unlined Rock Caverns

- Only a single storage was created for natural gas (Haje, Czech Republic). The named storage utilised a pre-existing very deep shaft. No experience exists for natural gas storage at common (shallow) depth.
- Decision to create the storage was very specific to local geology and the then present political situation.
- No experience with storage of pure hydrogen.

➔ fair (o)

Abandoned Salt Mines

- Only a single storage for natural gas was constructed yet (Bernsdorf, Germany). However, long operation time without disruption of operation has been realised until today.
- No experience with storage of pure hydrogen.

➔ fair (o)

Abandoned Limestone Mines

- No storages were converted to store high pressure gases yet. So far only exploration and testing of one mine in the USA (Norton Ohio) is known.

➔ poor (-)

Abandoned Coal mines

- Few high pressure storages were utilised as natural gas storage.
- All of the named storages have been decommissioned. At least one of them (Leyden) because of gas leakage.
- No experience with storage of pure hydrogen.

➔ **insufficient (- -)**

Pipe Storage

- Large experience with technology to store high pressure gas. Several pipe storages for natural gas are in operation for several years.
- Several pipelines for hydrogen are in operation in several countries and for several years.

➔ very good (+ +)

2.4 Working gas capacity

Salt Caverns

- High storage capacity is achieved by means of large geometrical volume per cavern (typical volume 500,000 m^3), large pressure range (about 120 bar) and high storage pressure due to the large cavern depth.
- Working gas capacity of a 500,000 m^3 cavern is about 4 Mio kg of hydrogen at common depth. Commonly multiple caverns are combined to form a cavern field.

➔ good (+)

Depleted Oil Fields, Depleted Gas Fields

- Variety of medium to very large storage capacity is feasible because of large geometrical volumes and large pressure range.
- Working gas capacities of up to 300 Mio kg of hydrogen may be feasible.
- Large capacity requires large content of working gas

➔ very good (+ +)

Aquifers

- Variety of medium to very large storage capacity because of large pore volume and large pressure range.
- Working gas capacities of more than 20 Mio kg of hydrogen may be feasible.
- Storage capacity can be varied, if only a reduced part on top of the aquifer is utilised.
- Large capacity requires large content of working gas, for commissioning of storage.

➔ very good (+ +)

Lined Rock Caverns

- Smaller volume per cavern compared to salt caverns. Working gas capacities of 1 Mio kg hydrogen might be feasible per cavern.
- A limited number of caverns may be combined. A combination of four caverns, as proposed in the Sofregaz study, would enable a working gas of 4.3 Mio kg hydrogen.
- Very large pressure range and thereby little share of cushion gas is feasible.

➔ fair (o)

Unlined Rock Caverns

- Range of small to medium volumes may be constructed. A working gas capacity of 4 Mio kg of hydrogen would be feasible in a cavern with the volume and pressure range of the Haje storage. Combining multiple cavities to a larger storage does not seem feasible.
- Maximum pressure is commonly low because of shallow depth and sealing technique (water management). Additional pressure range limitation due to shaft seal.
- Minimum pressure is commonly high to support the structure and limit the water inflow.

➔ poor (-)

Abandoned Salt Mines, Abandoned Limestone Mines

- Often large volumes in the range of several million cubic meters exist. One million cubic meter storage would allow about 3 Mio kg working gas.
- Limitation to maximum pressure due to shaft seal.

➔ good (+)

Abandoned Coal Mines

- Very large but geometrically complicated volumes.
- Pressure range limitation due to shaft seal.
- Maximum pressure is very low because of sealing technique (water management).

- Minimum pressure is commonly high to support the structure and limit water inflow.
- Little pressure range, because of pressure limitations and therefore high share of cushion gas.

➔ fair (o)

Pipe Storage

- Volumes in the range of several thousand cubic meters are much too small to significantly contribute to long term storage. E.g. the 12,000 m³ pipe storage in Lepoldau (Austria) would allow for only 42,000 kg of hydrogen working gas.
- Minimum pressure is influenced only by efficiency considerations to eventually avoid pressures below pipeline pressure.
- Very good pressure range.

➔ **insufficient (- -)**

2.5 Flexibility

Salt Caverns

- Open space in cavern (in contrast to porous rock matrix in a reservoir) allows for high gas flow rates.
- About ten times the working gas capacity can be turned over per year.
- Flexibility is high and only limited due to rock mechanical limitations. Operations at low pressures are limited in time; some operation times at high storage pressures may be required thereafter.

➔ very good (+ +)

Depleted Oil Fields, Depleted Gas Fields, Aquifers

- Depleted reservoirs are commonly utilised for slow seasonal storage but not for frequent turnovers, because of limitations due to the multi-phase flow in the pore matrix.
- Absolute rates can be high, depending on the number of wells. However, in relation to the storage volume, these rates are limited.
- One or two times the working gas capacity can be turned over per year by seasonal operation.

➔ fair (o)

Lined Rock Caverns

- Open space in cavern (in contrast to porous rock matrix in a reservoir) allows high gas flow rates.
- Multiple times the working gas capacity can be turned over per year.
- Flexibility is high since lined rock caverns do less depend on rock mechanical limitations.

- During withdrawal low temperatures need to be avoided by limiting the pressure rate, due to shallow depth and thus low rock temperature around the cavern.

➔ good (+)

Unlined Rock Caverns, Abandoned Salt Mines, Abandoned Limestone Mines, Abandoned Coal Mines

- Open space in storages (in contrast to porous rock matrix in a reservoir) allows for high gas flow rates.
- Flexibility is limited due to rock mechanical limitations of surrounding rock mass.
- Multiple times the working gas capacity can be turned over per year.

➔ good (+)

Pipe Storage

- Open space in pipes allows high gas flow rates.
- Multiple times the working gas capacity can be withdrawn and injected, even on weekly basis.

➔ very good (+ +)

2.6 Content of impurities in withdrawn gas and potential storage gas depletion

Salt Caverns

- Rock salt is inert to hydrogen. Additionally the contact area is small in relation to the storage capacity. Interbedded materials may produce minor content of impurities.
- Some brine will remain in the cavern and water will evaporate into the stored gas. A significant content of moisture needs to be removed by gas drying facilities.
- In very few cases there is a little inflow of hydrocarbons containing gases which may be embedded in the salt rock mass.

➔ very good (+ +)

Depleted Oil Fields

- Liquids will evaporate hydrocarbons and other fluids in the product, even after converting the field to a storage for longer durations. Mixing of residual liquid and gaseous hydrocarbons as well as associated materials with hydrogen may occur.
- Formation water will evaporate into the stored gas. Therefore a significant content of moisture needs to be removed by gas drying facilities.
- Chemical reaction between hydrogen and host rock may lead to development of gases like H_2S and depletion of hydrogen.
- Some experience with long-chain hydrocarbons at natural gas and town gas storages (depletion of methane during former town gas storage).

➔ poor (-)

Depleted Gas Fields

- Mixing of gaseous hydrocarbons and associated materials with hydrogen. However, mixing will reduce during continued storage operation.
- Formation water will evaporate into the stored gas. Therefore a significant content of moisture needs to be removed by gas drying facilities.
- Chemical reaction between hydrogen and host rock may lead to development of gases like H_2S and depletion of hydrogen.
- In some cases significant depletion of methane during former town gas storage.

➔ fair (o)

Aquifers

- Formation water will evaporate into the stored gas. Therefore a significant content of moisture needs to be removed by gas drying facilities.
- Chemical reaction between hydrogen and host rock may lead to development of undesired gases like H_2S and depletion of hydrogen.
- In some cases significant depletion of methane during former town gas storage. However, back then a share of CO and CO_2 was injected together with hydrogen. This would not be the case for future hydrogen storage.

➔good (+)

Lined Rock Caverns

- No impurities or moisture will occur due to technical surface of lining.

➔ very good (+ +)

Unlined Rock Caverns

- Due to water management water will be in contact with the stored gas; therefore a significant content of water can evaporate into the stored gas and needs to be removed by gas drying facilities.
- Limited content of impurities may occur due to possible reactions with the host rock of the cavern wall and potentially with embedded minerals. However, the contact area between host rock and gas is much smaller than for porous storages.
- Potential impurities due to inflow of mine gases need to be removed by gas cleaning facilities.

➔ good (+)

Abandoned Salt Mines, Abandoned Limestone Mines

- Rock salt and limestone are inert to hydrogen and will not produce impurities; additionally the contact area is small in relation the storage capacity.
- A limited content of impurities may occur due to possible reactions with embedded minerals. However, the contact area between host rock and gas is much smaller than for porous storages.

- Potential impurities due to inflow of mine gases need to be removed by gas cleaning facilities.

➔ very good (+ +)

Abandoned Coal mines

- Due to water management a significant content of water may evaporate into the stored gas and needs to be removed by above drying facilities.
- Impurities due to large inflow of mine gases need to be removed by gas cleaning facilities.
- Depletion due to biological or chemical reactions between hydrogen and host rock may occur.
- A limited content of impurities may occur due to possible reactions with embedded minerals. However, the contact area between host rock and gas is much smaller than for porous storages.

➔ poor (-)

Pipe Storage

- No impurities or moisture will occur due to technical surface of storage pipes. Therefore no gas treatment is required.

➔ very good (+ +)

2.7 Damage to the storage itself due to biological and chemical reactions

Salt Caverns

- Rock salt is inert to hydrogen, therefore no issues are expected.
- Utilised materials in gas storage completion will be designed to be hydrogen resistant.

➔ very good (+ +)

Depleted Oil Fields

- Pores of reservoir might be blocked by products from reactions between hydrogen and minerals from host rock or microorganism. This would lead to reduced production performance or discontinued operation of a well.
- Increased operational and monitoring effort to avoid production of remaining oil.
- Former production wells need to be hydrogen resistant. They may need to be modified or backfilled.
- No experience with pure hydrogen storage; yet all experience derive from town gas storage with share of CO or CO_2.

➔ poor (-)

Depleted Gas Fields

- Pores of reservoir might be blocked by products from reactions between hydrogen and minerals from host rock or microorganism. This would lead to reduced production performance or discontinued operation of a well.
- Former production wells need to be hydrogen resistant. They may need to be modified or backfilled.
- No experience with pure hydrogen storage; yet all experience derive from town gas storage with share of CO or CO_2.

➔ poor (-)

Aquifers

- Pores of reservoir might be blocked by products from reactions between hydrogen and minerals from host rock or microorganism. This would lead to reduced production performance or discontinued operation of a well.
- No experience with pure hydrogen storage; yet all experience derive from town gas storage with share of CO or CO_2.
- Utilised materials in gas storage wells and completion will be designed to be hydrogen resistant.

➔ poor (-)

Lined Rock Caverns

- Applied materials will be designed to be hydrogen resistant.

➔ very good (+ +)

Unlined Rock Caverns

- Applied materials will be designed to be hydrogen resistant.
- Possible reactions with cavern wall will not impact the storage itself significantly.

➔ very good (+ +)

Abandoned Salt Mines

- Rock salt is inert to hydrogen therefore no issues are expected that could significantly damage the storage.
- Utilised materials in gas storage completion and shaft seals can be designed to be hydrogen resistant.

➔ very good (+ +)

Abandoned Limestone Mines

- Limestone is inert to hydrogen therefore no issues are expected that could significantly damage the storage. Possible reactions will not significantly impact the storage itself.

- Utilised materials in gas storage completion and shaft seals can be designed to be hydrogen resistant.

➔ very good (+ +)

Abandoned Coal Mines

- If some parts of the mine support system remain inside the mine they might be influenced by hydrogen corrosion. This might lead to destabilisation of the mine building and rock fall.

➔ poor (-)

Pipe Storage

- Applied materials are designed to be hydrogen resistant.

➔ very good (+ +)

2.8 Exploration efforts

Salt Caverns

- Good knowledge exists about salt formations in most European regions, because of interest of salt industry and exploration for hydrocarbons which often are trapped below salt formations.
- Location specific data must be achieved by geophysical tests like seismic surveys and by drilling of exploration wells.
- Hydrogen caverns may be installed in an existing gas storage field; in this case only minor effort for exploration is required.

➔ good (+)

Depleted Oil Fields

- Good knowledge about specific formations due to previous exploration and production. The tightness of the formation against gases must be proven by exploration and laboratory testing.
- Very good information about behaviour of formation related to liquid hydrocarbons.
- Biological and chemical reactivity needs to be explored, if yet unknown.

➔ good (+)

Depleted Gas Fields

- Very good knowledge about specific formations due to previous exploration and production.
- Very good information about behaviour of formation related to gaseous hydrocarbons (pressure tests, etc.).
- Biological and chemical reactivity needs to be explored, if yet unknown.

➔ very good (+ +)

Aquifers

- Intense exploration with geophysical methods like seismic surveys and drilling of exploration wells is required.
- Based on surveys and rock samples a comprehensive reservoir characterisation program needs to be performed in order to explore the storage and fluid properties and even more for exploring the geometry and capacity of the aquifer.
- Concerning hydrogen storage also the biological and chemical reactivity shall be explored.
- Additionally drilled wells might be required to monitor the perimeter and over lying strata of the storage formation.

➔ poor (-)

Lined Rock Caverns

- Exploration is required to identify suitable geologic formations.
- In-detail exploration by seismic and pilot wells is required to analyse the stability of the host rock specifically.
- Issues with rock stability can be compensated by wall design, to a certain degree

➔ fair (o)

Unlined Rock Caverns

- Exploration by seismic and pilot wells is required to analyse the stability of the host rock.
- Testing of host rock is required to prove its gas tightness.

➔ fair (o)

Abandoned Salt Mines, Abandoned Limestone Mines

- Little exploration of geology is required, since cavity is already created and accessible.
- Analysis of walls is required to check for potential leaks and other issues.
- Additionally drilled wells might be required to monitor the perimeter and over lying strata of the storage formation.

➔ good (+)

Abandoned Coal mines

- Little exploration is required, since cavity is already created and accessible.
- Analysis of walls is required to check for potential leaks and other issues.
- Exploration wells might be required to evaluate feasibility of ground water management.
- Additionally drilled wells might be required to monitor the perimeter and over lying strata of the storage formation.

➔ fair (o)

Pipe Storage

- No exploration is required, since the storage can be constructed independently of the geology.

➔ very good (+ +)

2.9 CAPEX

Salt Caverns

- The specific investment costs (CAPEX[1] per working gas mass unit) are commonly somewhat higher than for depleted fields, however, they are much lower than for rock caverns.
- Cavern construction costs can be estimated well, because of the large experience with natural gas storage. The required modifications for hydrogen caverns compared to natural gas storage are minor.

➔ good (+)

Depleted Oil Fields

- Modifications for hydrogen storage might be required. However, the good knowledge about the formation enables accurate cost estimates. An element of uncertainty may be the adaptation of existing wells to hydrogen.
- Much more cushion gas than for depleted gas fields is required due to dissolving of gas in residual oil. Compared to salt caverns anyhow a larger share of cushion gas is required.
- Despite the high investment costs depleted fields achieve low CAPEX per working gas mass unit, due to the very large working gas capacity.

➔ good (+)

Depleted Gas Fields

- Modifications for hydrogen storage might be required. However, the good knowledge about the formation enables accurate cost estimates. An element of uncertainty may be the adaptation of existing wells to hydrogen.
- Compared to salt caverns a larger share of cushion gas is required for depleted gas fields.
- Despite the high investment costs depleted gas fields are commonly the storage option with lowest CAPEX per working gas mass unit, due to the very large working gas capacity.

➔ very good (+ +)

Aquifers

- Comprehensive and costly exploration is required to assess the general feasibility of the formation as well as to verify the tightness and quantify the size of the storage.

[1] capital expenditures

- Storage and monitoring wells must be drilled and continuously maintained.
- The storage volume might be used flexibly. However, large amounts of cushion gas must be injected for commissioning and can neither be withdrawn during operation nor de-commissioning. The share of cushion gas is larger than that of salt caverns and depleted gas fields.
- The specific investment costs for working gas of aquifer storages commonly are between the costs of salt caverns and depleted fields.
- The cost estimate accuracy is low, since it depends essentially on the outcome of the site exploration, which is difficult to estimate.

➔ good (+)

Lined Rock Caverns

- High labour costs arise during the excavation of access shafts or ramps and caverns. Lining and specially designed cavern wall enable high storage pressures even in shallow depth. Therefore the access shaft or ramp is short and less costly than for unlined rock caverns.
- The cavern wall construction requires large amounts of concrete and steel. Higher steel grades will probably be required for hydrogen storage, and thus increase the costs.
- The amount of cushion gas needed is small, due to the large pressure range.
- CAPEX per working gas mass unit of lined rock caverns is about five times as high as for salt caverns.
- Only a pilot plant has been constructed yet, therefore the accuracy of cost estimates is low.

➔ poor (-)

Unlined Rock Caverns

- High labour costs arise during the excavation of access shafts or ramps and caverns. Construction of a water curtain (galleries and many drill holes) is required and will further increase the construction costs.
- To achieve reasonable storage pressures a large depth of the cavity is required. This requires deep and costly access shafts.
- CAPEX per working gas mass unit for unlined rock caverns is probably higher than for lined rock caverns, due to the deeper access shaft and the required water curtain.
- Only a single plant has been constructed yet, therefore the accuracy of cost estimates is very low.

➔ poor (-)

Abandoned Salt Mines, Abandoned Limestone Mines and Abandoned Coal mines

- No construction costs for the excavation of the storage cavity is required.
- An investment for the shaft plug(s) is required.
- Large amount of cushion gas is required, due to the poor pressure range.

- Only very few and very specific storages have been constructed for each option, therefore the accuracy of cost estimates is very low. However, CAPEX is estimated to be between salt caverns and rock caverns.

➔ good (+)

Pipe Storage

- Compared to the other storage options discussed before, only very small sized storages can be constructed with limited CAPEX.
- CAPEX per working gas mass unit can be around 50 times higher than for salt cavern storages.
- Due to the high number of possible gas turnovers the costs can be redistributed to a large amount of produced gas.
- Construction costs may be estimated with good accuracy.

➔ **insufficient (- -)**

2.10 Static and dynamic stability of storage

Salt Caverns

- The unique properties of rock salt provide very good dynamic stability.
- Micro-fracs which may occur during operation will re-heal at high pressure stand-still periods due to specific rock salt properties.
- The cavern geometry can be designed and constructed especially to bear dynamic loads of frequent gas turnovers.

➔ very good (+ +)

Depleted Oil Fields and Depleted Gas Fields,

- Seal and pore matrix near the well bore might be damaged if too high rates and thereby high dynamic pressures occur.

➔ good (+)

Aquifers

- Formation pressure increases above in-situ pressure when gas is initially injected during commissioning.
- Seal and pore matrix near the well bore might be damaged if too high rates and thereby high dynamic pressures occur.

➔ good (+)

Lined Rock Caverns

- Limited capability of host rock to bear dynamic loads is compensated by specifically designed cavern wall.
- The cavern geometry can be designed and constructed especially to bear dynamic loads of frequent gas turnovers.

➔ very good (+ +)

Unlined Rock Caverns

- Host rock has limited capability to bear load gradients. Cracks may be induced and can then lead to leakages or higher water/brine inflow.
- The cavern geometry can be designed and constructed especially to bear dynamic loads of frequent gas turnovers.

➔ good (+)

Abandoned Salt Mines, Abandoned Limestone Mines, Abandoned Coal mines

- Host rock has limited capability to bear load gradients.
- Cracks may be induced and can then lead to leakages or water/brine inflow.
- Geometry is designed for static ambient pressure and not for dynamic loads.

➔ fair (o)

Pipe Storage

- Steel can perfectly bear dynamic loads of frequent gas turnovers.
- Storage can be designed to match the requirements (e.g. by wall thickness of pipes).

➔ very good (+ +)

2.11 OPEX[2]

Compressor costs are not considered because they are common to all storage options and most storages are operated in the same pressure regime.

Salt Caverns

- On the surface operational costs result from gas dehydration, however, no gas cleaning is required.
- Salt caverns require only little maintenance.
- Monitoring relates to observation of storage pressure only. In addition after several years of operation surveys of the cavern need to be performed.

➔ very good (+ +)

[2] operational expenditures

Depleted Oil Fields

- Gas dehydration as well as gas cleaning from impurities like e.g. gaseous and liquid hydrocarbons is required. Gas cleaning efforts will probably not decrease much during the storage life time.
- Monitoring of pressures and wells is required, as well as continued reservoir simulation.
- Efforts due to potential periodic ingress of oil will lead to increased operational costs.

➔ fair (o)

Depleted Gas Fields

- Gas dehydration as well as gas cleaning from impurities like e.g. gaseous hydrocarbons is required. However, the content of impurities may decrease with duration and intensity of storage operation.
- Monitoring of pressures and wells is required, as well as continued reservoir simulation.

➔ good (+)

Aquifers

- Gas dehydration as well as gas cleaning from impurities like e.g. carbon dioxide is required.
- Monitoring of pressures and wells is required, as well as continued reservoir simulation.

➔ good (+)

Lined Rock Caverns

- Neither gas dehydration nor gas cleaning is required.
- Monitoring of storage pressures, access shaft seal and down-hole instrumentation is required.

➔ very good (+ +)

Unlined Rock Caverns

- Gas dehydration as well as minor gas cleaning from impurities like mine gases is required. Monitoring of storage pressures and operation of the access shaft seal is required, as well as monitoring of the water curtain.
- Operation of water management requires monitoring of wells and energy to run the water pumps.

➔ fair (o)

Abandoned Salt Mines and Abandoned Limestone Mines

- Gas dehydration as well as minor gas cleaning from impurities like e.g. mine gases is required.
- Monitoring of storage pressures and the access shaft seal is required.

- Operation of monitoring wells might be required.
- The accuracy of the OPEX estimate is very low, since only little information is available.

➔ good (+)

Abandoned Coal mines

- Gas dehydration as well as gas cleaning from impurities like mine gases is required.
- Monitoring of storage pressures and the access shaft seal is required.
- Operation of monitoring wells might be required.
- Monitoring of storage pressures and operation of the access shaft seal is required, as well the monitoring of the water curtain.
- Operation of water management requires monitoring of wells and energy to run the water pumps.
- The accuracy of the OPEX estimate is very low, since only little information is available.

➔ poor (-)

Pipe Storage

- Neither gas dehydration nor gas cleaning is required.

➔ very good (+ +)

3 Benchmarking results and summarised ranking of the investigated storage options

The ultimate aim of Work Package 3 is to identify those geological storage options which have the greatest potential for the practicable realisation of high pressure hydrogen storages, and then to select the option to be taken into consideration in the case studies undertaken in Work Package 6 "Representative Case Studies with a focus on salt cavern storage".

The previous Deliverables 3.1 and 3.2 describe the general options available for the underground storage of high pressure gas, as well as the development and application of criteria, including weighting. The present Deliverable evaluates the options to provide a benchmarking. Table 3-1 summarises the ratings and the weighting system to deliver the combined rating for all criteria considered and thus the benchmarking for all storage options.

Number one in the ranking is the **salt cavern** option, see Table 3-1. This is not surprising because natural gas as well as hydrogen have already been successfully stored in salt caverns for many decades. The outstanding properties of salt caverns are the high integrity or tightness, the inertness of the rock salt to hydrogen, the high flexibility, and the relatively moderate investment and operating costs. However, the realisation of storage caverns naturally requires the availability of suitable salt formations, and specifically salt formations with the appropriate lateral and vertical thickness, depth, and purity. Because suitable salt deposits of this kind are geographically not evenly distributed, and do not necessarily occur in the regions with the highest demand for such caverns, it is also essential to take into consideration other storage options.

Second rank is occupied by the **depleted gas field** option. Depleted gas fields are the dominant option world-wide for the storage of natural gas, in particular for seasonal – in other words, less flexible – applications. Their popularity is due to the use of already existing reservoirs and the proven tightness of the reservoirs over geological time periods with respect to hydrocarbon gases. Experience with the storage of hydrogen is limited to the former storage of town gas which contains high concentrations of hydrogen.

Table 3-1: Benchmarking results for high pressure hydrogen storage options

	Salt Caverns	Depleted Oil Fields	Depleted Gas Fields	Aquifers	Lined Rock Caverns	Unlined Rock Caverns	Abandoned Salt Mines	Abandoned Limestone M.	Abandoned Coal Mines	Pipe Storage	Weighting coefficient
Safety											
Tightness of Storage	++	+	++	++	+	-	o	-	- -	++	2
Feasibility to prove tightness	++	++	++	+	o	-	- -	- -	- -	++	2
Practical experience	++	o	+	+	o	o	o	-	- -	++	2
Technical feasibility											
Working gas capacity	+	++	++	++	o	-	+	+	o	- -	1,5
Flexibility	++	o	o	o	+	+	+	+	+	++	1,5
Content of impurities	++	-	o	+	++	+	++	++	-	++	1,5
Damage to storage by reactions	++	-	-	-	++	++	++	++	-	++	1,5
Investment costs											
Exploration efforts	+	+	++	-	o	o	+	+	o	++	1
CAPEX	+	+	++	+	-	-	+	+	+	- -	1
Operation											
Static and dynamic stability	++	+	+	+	++	+	o	o	o	++	0,5
OPEX	++	o	+	+	++	o	+	+	-	++	0,5
Rank	**1.**	5.	**2.**	**3.**	4.	6.					

Rating:	
very good	++
good	+
fair	o
poor	-
insufficient	- -

If depleted gas fields are used to store hydrogen, it is likely that the hydrogen will be contaminated with residual hydrocarbon gas from within the reservoir, which will then need to be cleaned up upon withdrawal by passing the gas through appropriate surface installations. A more critical problem is considered to be the possible reaction of the hydrogen with the in situ inventory of different rock types and microorganisms like bacteria. Reactions of this kind could lead to hydrogen depletion as well as blockages in the fine pore spaces of the reservoir. A number of R&D projects are currently being implemented looking at this important aspect. Depleted oil reservoirs, however, only play a subordinate role compared to depleted gas reservoirs because of problems with the higher hydrocarbon components in the residual oil.

Third rank is occupied by **aquifer formations**. These also play a major role world-wide in the storage of high pressure natural gas. Compared with depleted gas fields, the ranking for this storage option is only slightly lower with respect to hydrogen. Experience with the storage of hydrogen in aquifer formations is restricted to the former storage of hydrogen-rich town gas. Unlike depleted reservoirs, a considerable amount of geological and reservoir engineering exploration needs to be undertaken in the case of aquifer formations to evaluate the general feasibility, the storage capacity and behaviour, and especially the integrity. On the positive side, no residual hydrocarbon gases need to be considered in the equation. With respect to the possible reaction of hydrogen with the in situ inventory, the same risks exist here as referred to under the depleted gas reservoirs. Looking at depleted gas reservoirs and aquifer formations in more detail as a part of this study could be useful because, when combined with the regions for salt caverns, the other areas in which there are depleted gas reservoirs and aquifer formations already cover a large part of the EU countries considered in this study.

Lined rock caverns have a number of favourable properties in principle, such as the storage gas only coming into contact with the metal lining. However, to date, only one pilot cavern for natural gas has been successfully realised so far in Sweden. A full-scale storage is currently being planned in Switzerland. A critical aspect is the permanently pressure-tight lining of the cavern with welded metal sheets, and verifying the integrity before staring operations and during operations. Unlike the other storage options, the integrity relies solely on the metal lining with a wall thickness of only a few centimetres. Lined rock caverns may mainly be of interest in regions which have neither suitable occurrences of salt formations, nor depleted reservoirs or aquifer formations, but large areas of homogenous hard rock, such as in Scandinavia and certain regions in the Alps. It is feasible that in the long term, lined rock caverns could become an interesting addition in certain regions to salt caverns and natural reservoirs.

To date, an **unlined rock cavern** has only been used for natural gas storage in one special case. The reliable, long-term sealing of an originally not absolutely tight rock by realising a limited amount of water inflow (water management) to store a flammable gas under pressure, as well as verifying the integrity, are extremely challenging in practise. Regions with rock formations which could be suitable for constructing an unlined gas storage of this kind might do better to favour the lined rock cavern alternative.

Abandoned salt or **limestone mines**, former salt mines in particular, which have not flooded, are regularly proposed as potential candidates for gas storage. The motive is the availability of large, stable unused cavities. However, almost all salt mines have water or brine inflows to a greater or lesser extent. Complete tightness appears unlikely. In addition it is almost impossible in practise to confirm the tightness, even when this is assumed, because the shafts would first have to be sealed up with complex gas-tight plugs, and a pressure test with compressed air for instance, would probably not support the degree of accuracy required to properly carry out such an integrity test. A number of abandoned salt mines became available in the former German Democratic Republic after reunification and were investigated to assess their potential for the storage of natural gas: however, not a single project was realised even after undertaking extensive studies.

Abandoned coal mines are barely worth consideration for subsequent use as hydrogen storages even though a few mines have been used temporarily in the past for the storage of natural gas. Modern coal mines are operated using the caving method and therefore leave behind almost no storage cavities. And even if stable cavities were available, it would be almost impossible to verify the integrity because hydrogen would be adsorbed by the coal and therefore render inaccurate the mass balance calculation upon which integrity tests are based.

Pipe storages seem to be a realistic option to store pressurized hydrogen. However, very high specific investment costs and footprint do not allow large scale storages.

Conclusion: In the following study (Deliverable 3.4), the primary option is salt caverns, followed by depleted gas fields and then aquifer formations.