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**CLEEN - CCS**
**Task 4.2.1 - Terminals and Intermediate storage**

**Deliverable D406: Economy of intermediate storage a as part of CO2 terminal**

Deliverable

**Cleen Ltd.**
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# CLEEN - CCS
# Task 4.21 - Terminals and Intermediate storage

# Deliverable D406: Economy of intermediate storage as a part of CO2 terminal

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**CO2 - Terminals and Intermediate storage**
**Deliverable D406: Economy of intermediate storage as a part of CO2 terminal**

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## Abstract

This document is intended as an internal working paper of CCS WP 4.2.1. The document includes the preliminary results of transport and underground intermediate storage possibilities of CO2. Potential underground storage technologies as well as suitable underground solutions for CO2- storage have been investigated.  Abandoned mines have been checked as potential intermediate CO2-storages, but in most cases they are not suitable as intermediate storages of CO2. Kilpilahti oil industry area has been investigated as potential environment of CO2 intermediate underground storage. As an intermediate underground storage case a 50 000 m3 storage unit has been investigated. The investment cost of storage unit has been estimated and compared to the investment cost of above ground modular steel tank group by same volume.

The results underpin the commonly assumed economic benefits from investing into caverns instead of modular on-ground tanks for large, over 50 000 m3 intermediate storages for CO2. The economic difference between the storage modes is a result of significantly lower investment cost per storage volume of a cavern compared to steel tanks. The operational and maintenance costs can be assumed to represent only a minor share of the annual cost of a storage facility. The annual costs from reliquefaction of boil-off CO2 from both cavern and tank storages were of the same order of magnitude compared to the investment costs. However, the subject does not appear often in the scientific literature, and the available data does not provide basis for a robust analysis. The risk of error or misjudgement remains high.

Helsinki, February 2013

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# 1  Introduction

$CO2$ capture and storage (CCS) is important also in Finnish point of view based on the following background:
- Finland has large point sources, which are mainly located in coastal areas, figure 1
- Only solution for many industrial facilities
- Scenario calculations show, that $CO2$ emissions could be reduced in Finland 10-20 Mt using CCS by 2050
- Capture, processing and transport technologies emphasized in a country with no final underground storage options

The evaluation of geological intermediate storage options is the focal point of Task 4.2.1. The site selection criteria for the underground storage of $CO2$ are to be created based on techno-economic understanding of intermediate storages and selection of geologically suitable sites in the vicinity of selected $CO2$ producing plants for detailed investigations. Assessment of terminal-based transportation solutions under Finnish conditions is further based on this.

Conditions and functional requirements for geological intermediate storages will be defined. Potential of geological intermediate storages in Finland will be evaluated based on preliminary selected CCS cases. If there are abandoned mines or for instance unused underground oil or gas storages in near environment of potential CCS-cases, these will be studied as potential intermediate storages for $CO2$.

# 2  CO2- capture, logistic, intermediate storage in Finland

## 2.1  CO2- hot spots in Finland

The majority of large Finnish $CO2$ emission point sources are spread out along the complete length of the coastline. Without considering the lengthy transport distances, this does provide two benefits; most of the captured $CO2$ flows could be transported to final storage sites by ships as an alternative to pipeline transportation, and a single trunk pipeline could be built to collect the majority of emissions in the future (Figure 1).

Although the emission sources are spread out, some hot spots of large $CO2$ emissions can be identified. In the report by Teir et al. (2010) such hotspots were identified at the north end of the Bay of Bothnia, at the industrialised region between Helsinki and Porvoo, and as an example of inland sources of biogenic $CO2$ the forest industry of south-east Finland. These groups are highlighted in red outline in Figure 1.

The northern Bay of Bothnia incorporates a variety of industrial activities, coupled with similar portfolio on the Swedish side of the bay. Among the point sources is the largest $CO2$ emitter of Finland, the steel mill in Raahe. Another large steel mill is situated in Tornio. The area also has energy industries and

significant pulp and paper production. Towards the south, on the coastline of the Bay of Bothnia is situated a large pulp and paper mill and further south fossil fuel based power production at the Kvarken region.

Further south on the coast of the Sea of Bothnia extensive fossil power production takes place. Among the facilities is the Meri-Pori condensing power plant, one of the country's largest point sources of CO2. Other energy industries are also spread across the near-by coastline, along with mixed activities of pulp and paper production, oil refining and cement and lime production.

The distances between large CO2 point sources shorten towards the coastline of the Gulf of Finland. The local activities are dominated by energy industries and oil and gas refineries. The refinery at Porvoo Kilpilahti is among the largest point sources here. Aside from energy and oil refinery industries, one iron and steel production plant is situated in Koverhar in the western shore of the gulf. The area consisting of the regions of Helsinki and Porvoo form a definitive CO2 hot spot. The biogenic sources from the forest industries in south-eastern Finland are within reasonable pipe transport distances to the Porvoo area, an interesting point to consider regarding the possible future viability of BioCCS.

## 2.2  Logistic and need for CO2-intermediate storage

Cost efficient logistics would be required to enable CO2 capture from Finnish point sources for the purposes of geological storage. The transport distances would be significant, as no domestic storage capacity is available. Moreover, suitable geological formations are unlikely to be discovered in the future [Solismaa, 2009 & Teir et al. 2011].

Within the context of EU's emission trading scheme (EU-ETS), CO2 capture, transportation and storage must follow the scope and prohibition in the directive 2009/31/EC (CCD Directive). The Article 2 (1.) limits the application of the CCS Directive to geological storage of CO2 in the territory of Member States and their exclusive economic zones and on their continental shelves. Therefore, the storage sites would have to be selected within the EU and European Economic Area (EEA), if and when the CCS Directive is included in the EEA Agreement.

For the purposes of geological storage of CO2, a suitable porous rock sediment formation at adequate depth is needed. These are namely saline aquifers and depleted oil and gas fields, found both on- and off-shore. The nearest operational CO2 storage sites to Finnish point sources are situated off-shore at the Utsira formation in the North Sea and at the north-east part of the Norwegian Sea.

The closest CO2 storage potential in aquifers within EU has been reported to be found at least on-shore in the northern parts of Poland and Germany and in southern Denmark. Some evidence proposes an interesting off-shore potential exists in the southern part of the Baltic Sea. [EU GeoCapacity Project, 2009].

A pipeline from the northernmost point sources of Finland to the coast of Norwegian Sea would range approximately 800 km, as long as the longest existing CO2 pipeline in the North America [Chandel et al. 2010]. A pipeline

towards the North Sea would involve greater set of challenges, including off-shore sections and laying the pipe across the well-populated part of Sweden. Such a pipeline would have to cross the Gulf of Bothnia from west coast of Finland into Sweden, continue towards the strait of Skagerrak and onwards off-shore again to the receiving terminal on the west-coast of Norway. Excluding connections to capture plants and storage sites the total range of such a pipeline, connecting the exporting and importing terminals, would amount to around 800 km of off-shore pipeline and 450 km of on-shore pipeline. If the exporting terminal in Finland would be situated near the large $CO_2$ point source of Meri-Pori, the length of the pipeline would be very similar to the on-shore pipeline that would be needed to connect the same terminal to an importing terminal on the shore of The Norwegian Sea.
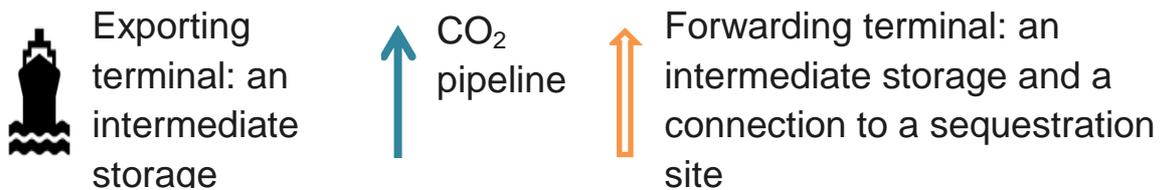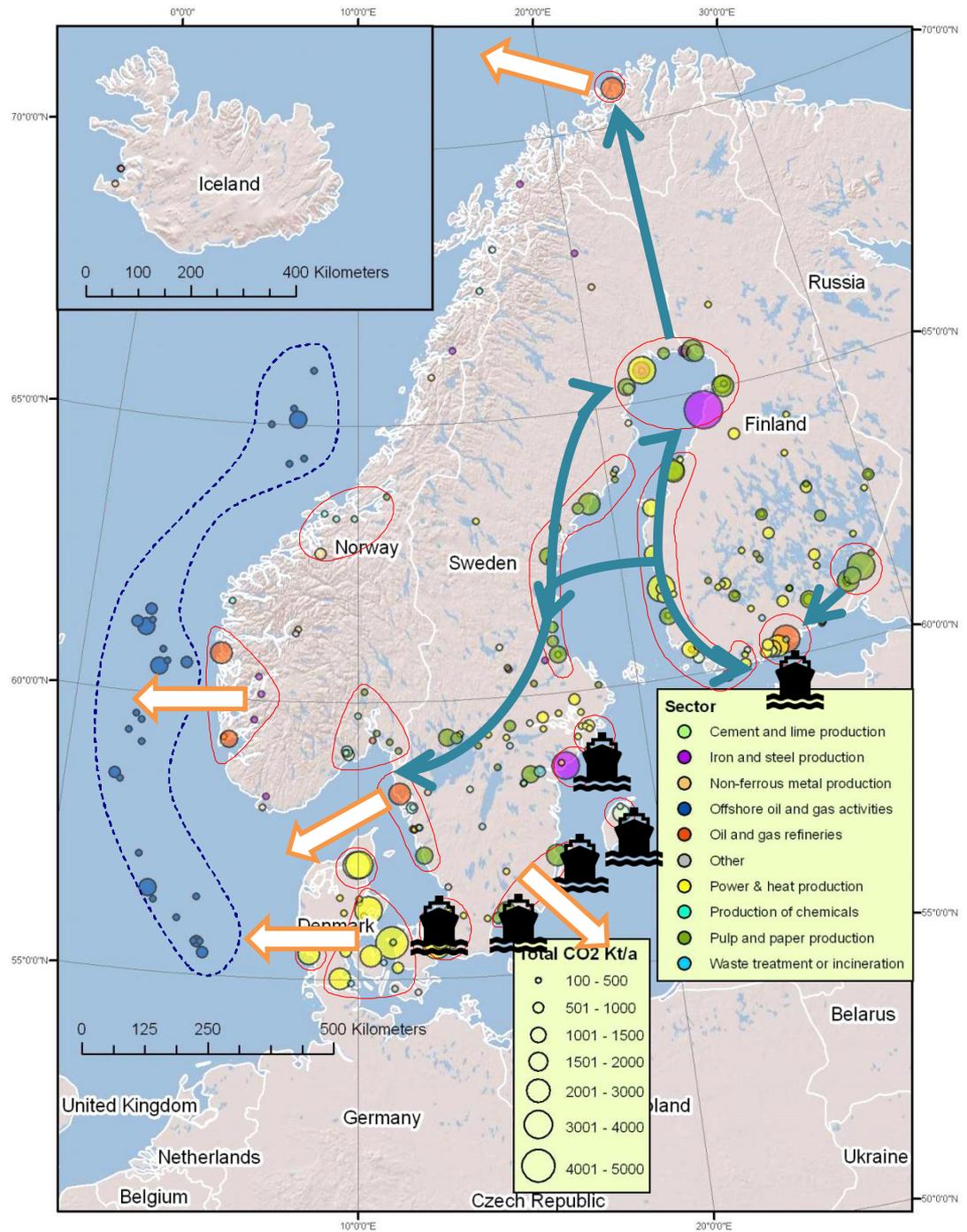
*Figure 1: Possible future CO2 flow routes from sources to sinks in the Nordics. (Based on material presented in VTT Research Notes 2556 (Teir et al. 2010)).*

By ship, the range from the Finnish coast to a receiving terminal in the Utsira area on the North Sea would amount to around 1 700 - 2400 km one way. Assuming a cruising speed of 15 knots and on- and off-loading times of 24 h, the journey from the exporting terminal to the destination and back would take roughly 8 to 10 days for a tanker.

The estimates of costs of CO2 transportation from Finnish point sources to geological storage sites on the North Sea and Barents Sea indicate that CO2 transport by ships should be preferred over pipelines in the initial stages of CCS implementation [Teir et al. 2011]. Aside from delivering better transport economy at capture amounts of below 10 Mt/a, the ship transport infrastructure would be faster to establish, would result in a more flexible transport system and would require less intensive permitting and rights-of-way acquiring procedures. Legal and regulatory gaps still exists, these are covered in the WP 1.1 of the CCSP.

Shipping solutions require by default an intermediate storage for the collected CO2. The storage facilities can either be cylindrical steel tanks above ground or excavated rock caverns deep below ground.

# 3 Functional requirements for CO2- intermediate storage

## 3.1 Pressure and temperature

CO2 is at its densest form near the triple point at 5.2 bar and -56.6 °C, weighing some 1 200 kg/m3. Near the critical point, at 72.8 bar and 31°C, the density of CO2 is 600 kg/m3, merely a half of the density near the triple point. The properties of CO2 are the most important factors in determining the functional requirements of a CO2 intermediate storage.

To minimize the required storage volume, a temperature close to, but reasonably above to avoid solid ice formation, -56.6 °C at triple point should be selected. The same applies to pressure, for which a reasonably higher level than the 5.2 bar should be selected. The pressure should be as close as possible, but safely above the saturation line to avoid vapour formation.

The choice of pressure and temperature of the stored CO2 at the terminal depends also on the storage solution. If the storage consists of modular cylindrical steel tanks, which are heat insulated from the environment, the lowest possible pressure might be preferred to minimize the valuable storage volume and land area for the storage tanks. Avoiding higher pressures also lowers the material requirements for the storage tanks. As the energy required in liquefaction of CO2 increases in lower pressures, the design temperature and pressure in the intermediate storage must be optimised accordingly. This case specific need for optimization applies also to the temperature and pressure during the actual shipping.

## 3.2  Storage capacity

The design of a CO2 logistic infrastructure is in reality case specific. Ultimately, the need for intermediate storage capacity depends on the number of tankers, time interval between the loadings, seasonal fluctuations in the captured amount of CO2 and both intended and unanticipated changes in the operational tanker fleet. The deadweight of each tanker is designed to meet the maximum flow rate of CO2 from the liquefaction plant. Therefore, the theoretical operational capacity of the intermediate storage needs only to match the capacity of a single tanker. Some buffer capacity is however needed, along with a sufficient headspace for the boil-off gas. Taking this matter into account, as a rule of thumb the intermediate storage capacity should be 1.5 times the capacity of a single tanker in the CO2 carrier fleet.

Although the largest currently operating tankers, capable of transporting liquefied CO2, have capacities of around 10 000 t, larger vessels, at least up to capacities of 50 000 t, can be considered as commercially available [IPCC 2005, IEA 2004 & IEA 2008].  The range of needed intermediate storage capacity therefore is around 15 000 – 75 000 tCO2. This corresponds to the volume of 12 500 – 125 000 m3, depending on the design pressure and temperature.

## 3.3  Integration to the terminal infrastructure

Other functional requirements for the storage facilities are set by the terminal infrastructure and the overall transport process. The storage tanks must be in the proximity of the liquefaction plant, where the boil-off CO2 has to be returned for re-liquefaction. The boil off cannot be eliminated due to heat flow between the storage tanks or caverns and the environment. The storage must be connected to the loading equipment as well and designed to allow sufficient discharge flow rates. For example, loading a tanker of 25 000 deadweight tonnage in 24 h, a flow rate of over 1 000 t/h is needed. If the CO2 is stored at the terminal in a different temperature and pressure than designed for the tanks on-board the ships, a flash or compression and heat exchange process is needed prior to the loading of the CO2.

The CO2 storage facilities require both energy and space at the site, depending whether the storage is above or below ground. One of the few occurring designs in literature of a CO2 ship terminal area was presented in a document prepared by Elsam A/S, Kinder Morgan CO2 Company L.P. and New Energy, Statoil (2003). The total area of the facilities including the liquefaction plant and the above ground cylindrical storage tanks was 200 m by 400 m, of which the tanks occupied an area of 80 m by 200 m.

The energy intake of a liquefaction process depends on various environmental and process factors, including the input pressure and temperature of the gas. According to Aspelund & Jordal (2007), in order to liquefy 1 ton of CO2 from 1 bar and ambient temperature, 105 kWh of energy is needed. In addition to the liquefaction of the CO2 entering the terminal, the re-circulated boil-off gas adds to the load on the liquefaction plant. The boil-off from an isolated tanks amounts to 0,2 % of capacity per day (IEA, 2004).

## 3.4 Functional requirements for CO2- intermediate storage in rock caverns

Based on the phase diagram of CO2 (Figure 2), general bedrock and groundwater conditions in Finland and general functional requirements of CO2 intermediate storage described in follow chapters the detailed functional requirements for geological intermediate storages in Finnish bedrock conditions can be described:

Storage temperature (T)                   - (50 - 30) $^o$C
Storage pressure (P)                       10 - 20 bar (1 - 2 MPa)
(100 – 200 m below Gw-surface)
Storage volume in rock (V)           > 50 000 m3

By these design requirements the CO2- storage in rock has several similarities with refrigerated LNG- and LPG- gas storage technologies in unlined rock caverns. The extra challenge with the CO2-storage is the need for both refrigerating and pressurizing of the storage. The temperature - pressure relation of liquid CO2 is the most important consideration when designing a intermediate rock cavern CO2 storage and the chosen temperature - pressure condition for the liquid CO2 will be dependent on many factors: The frozen fractures/zone should prevent contact between CO2 and groundwater. The hydrostatic pressure should be high enough to keep the CO2 from escaping the storage (probably slightly higher than the storage pressure). The forming of a frozen zone around the storage should also be taken into account when planning the storage depth. Rock quality, groundwater conditions and infrastructure requirement may also create design margins with respect to pressure and temperature. Finally the capital and operational costs of the storage should be related to the available storage conditions.
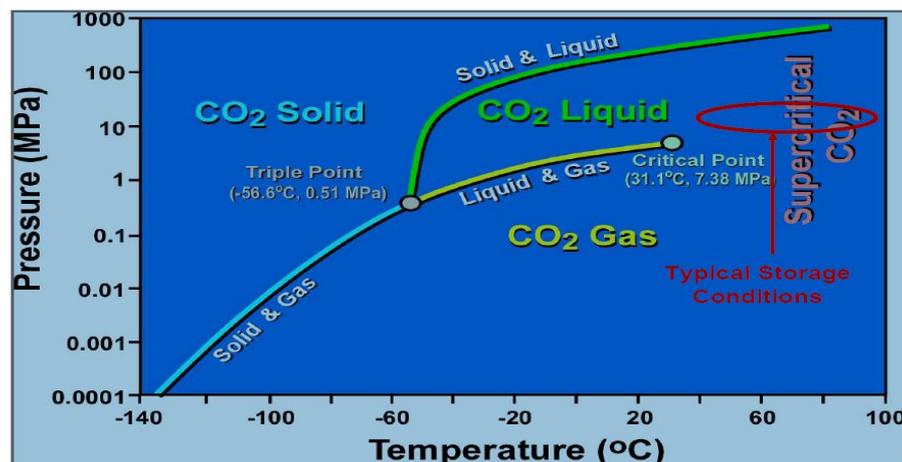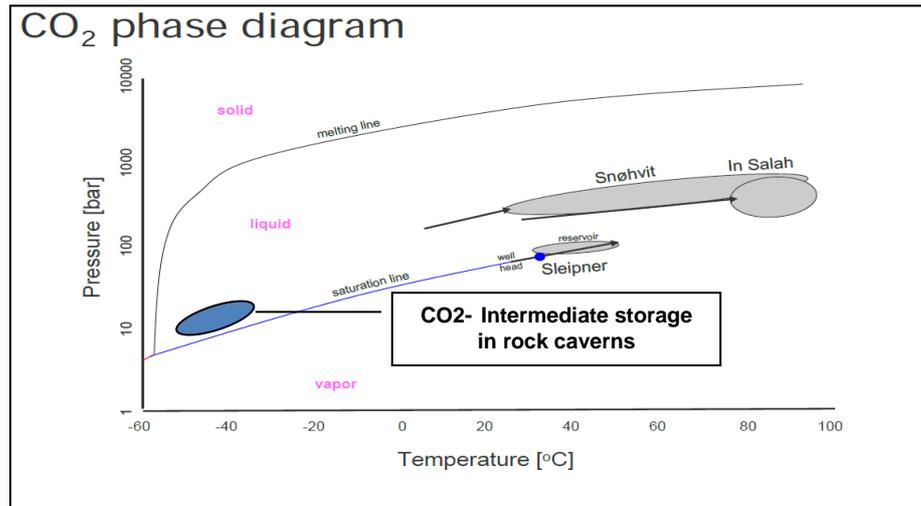


Figure 2 a

*Figure 2 b*

*Figure 2. CO2-phase diagram 21a) including a suitable intermediate storage environment for rock caverns (2b).*

Other considerations that need to be taken into account are the possible need for monitoring of the intermediate storage and CO2 background value surveys prior to operation. At the moment the intermediate storage technology and shipping is not included in the EUs CCS directive but some sort of monitoring will presumably be demanded. The cooling and insulation of the storage by the freezing fractures probably prevents reactions between rock, water and CO2 but could be site specific and will probably need to be investigated.

## 3.5  Conventional storage in cylindrical semi-pressurised steel tanks

CO2 is used globally in various industrial processes, for instance in food industries and fertilizer production. Larger amounts of the gas are stored conventionally in cylindrical steel tanks, chilled sufficiently to allow the CO2 to reside in a liquid state under moderate pressure. As the tanks grow bigger in capacity they are likely to be installed horizontally above ground. In CCS application, involving presumably larger CO2 storage units than in other industries, the investment cost of the storage facility would have to be minimized over the total amount and capacities of single tanks. Increasing the capacity of a single cylindrical tank can either be accomplished by increasing the length or diameter of the tank. When the diameter is increased, the wall thickness has to be fortified accordingly. This leads to both economic and technical restrictions at a certain point. However, as the overall capacity of the intermediate storage facility can be designed by selecting virtually any amount of steel tanks, the investment cost can be presumed to increase linearly with increasing capacity.

The largest cylindrical tanks for CO2 storage occurring in literature have volumes of 3 000 m3 (Svensson et al. 2004, Aspelund et al. 2009). The investment cost of a single tank are ranging from 2,94 M€(Aspelund et al. 2009) to 6,5 M€ (Svensson et al. 2004). When adjusted only with the Euro-area inflation, the investment in 2013 would range from 3,15 M€ to 7,85 M€.

According to a document prepared by Elsam A/S, Kinder Morgan CO2 Company L.P. and New Energy, Statoil (2003) an intermediate storage of CO2 consisting of 10 tanks of 3 000 m3 each would occupy an area 80 m wide and 200 m long next to the pier at the shipping terminal. A single tank would be approximately 70 m in length and 8 m in diameter, including the insulating materials.

# 4   Storage of CO2 in rock caverns

## 4.1   Experiences of oil and gas storage in rock caverns

Refrigerated LNG-storages has not yet built anywhere in rock, but some refrigerated LPG-storages are in active use. Rock caverns within the LPG industry are constructed in two different ways, either as pressurised or as cooled caverns. If the caverns are intended for storage of CO2, these techniques must be combined to create favourable conditions with respect to pressure and temperature for the CO2. The cost for building a rock shelter depends mainly on the rock quality. Poor rock quality increases the need for lining and reinforcement of the rock, which increases costs [14] Söder P. SwedPower AB—Rock shelter construction, private communication, 2002. [14].
(Lähde: ks. artikkelit kansio)
http://www.sciencedirect.com/science/article/pii/S0196890403003662

Steel tanks are area and space consuming installations because of the limitations of the maximum size of individual tanks. Storage of large amounts of CO2 may therefore require solutions that do not need very large surface areas, such as rock caverns. Rock caverns for intermediate storage of CO2 will imply new application for this technology, which has been used years with regard to storage for instance propane (ECDN 2005).

Rock caverns are regularly used for example for LPG, but have so far not been qualified for storage of CO2. Rock caverns should be constructed deep (100 - 200 m below surface). They may be with or without lining and they are until now mostly thought of as a concept suitable for crystalline rocks (ECDN 2005).

Unlined rock caverns have been used for decades to store a wide range of low vapor pressure products, mostly liquid such as crude oil, butane and propane. Since the host rock is never completely impervious, product confinement within the cavern is achieved through water curtain technique. When water is continuously flowing towards the cavern, so the stored product cannot escape and migrate out of the cavern (Sofregaz 1999).

The idea of lined rock cavern (LRC) consists of four components. The rock mass surrounding the cavern is the pressure-absorbing medium. A pressure-transferring concrete layer is cast between the lining and the rock. The gas-tight lining material must be chemically resistant to gas and to possible condensates and impurities. A drainage system is installed outside the cavern, between rock wall and concrete. Its function is reducing the hydrostatic pressure of groundwater. It is needed only if the cavern is depressurized for maintenance for example (Sofregaz 1999).

## 4.2  Pressurized LPG cavern storage

In pressurised caverns the LPG is stored at the ambient rock temperature, 5 – 20 $^{o}$C, depending on location and at a corresponding vapour pressure 7 – 10 bar. The cavern has to be located deep enough to achieve a ground water pressure around the cavern which is higher than the maximum storage pressure. Some ground water is always seeping into the cavern and is continuously pumped out.

The pressurized gas storage is built so far beneath the ground water surface that the hydrostatic pressure of the ground water in the storage walls is higher than the pressure inside the storage. This prevents the gas from leaking to cracks in the rock. The pumps are located inside a protective pipe. When the pumps need maintenance the protective pipe is filled with water and thus the pressure inside the pipe and the pressure inside the storage as well as the hydrostatic pressure of the liquid LPG are in balance. Then the pumps can be lifted from the storage system without having to decrease the pressure inside.
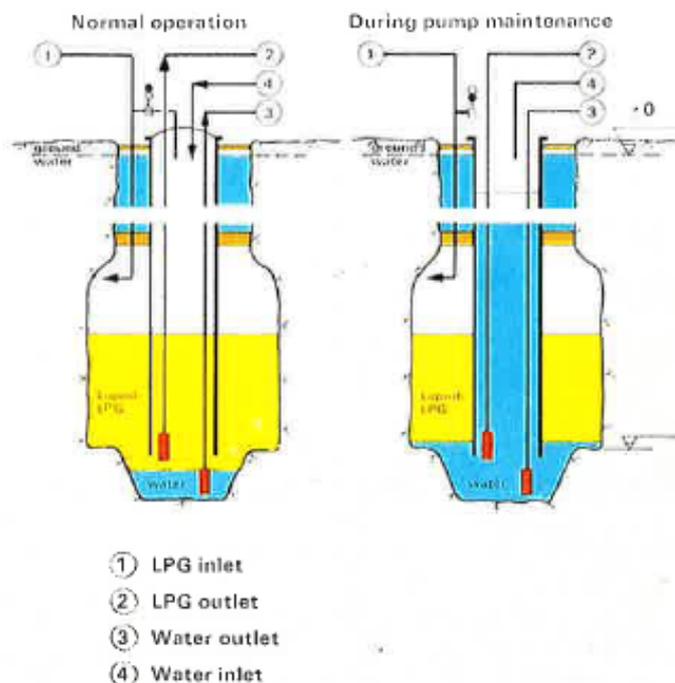


*Figure 3.  Principal flow scheme for pressurized LPG-storage (YIT-brochure,1984).*

Neste Oyj has several oil caverns at its Porvoo Works (Kilpilahti). In 1987 two unlined caverns were constructed for gas concentrate and liquefied propane (100 000 and 50 000 m3). The caverns operate under pressure of 6.5 and 10 bars and they both operate on the fixed water-bed principle. The vault level of the light condensate is over 100 meters and that of the propane cavern over 140 meters below the sea level. The ambient rock temperature is about +8 to + 10 oC (Neste Engineering 1986). A schematic picture of pressurized LPG storage is shown in Figure 4.
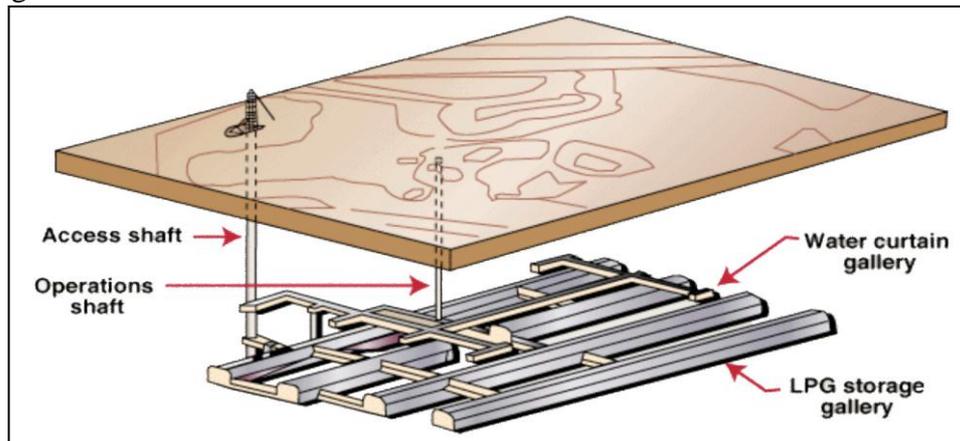


*Figure 4. A schematic view LPG storage locating in Sydney. The capacity of storage is 130 000 m³/65 000 tons. The dimensions of storage tunnels are 14 m/11 m/230 m (B/H/L) and the tunnels for water curtain are 4 meters in breadth and 3.5 m high (The Allen Consulting Group 2009).*

## 4.3 Refrigerated non-pressurized gas cavern storage

Non-pressurized gas storage is refrigerated to a temperature keeping the product in liquid state in the pressure of the open air. No seepage water can possibly enter the system because it will be frozen in cracks in the rock.



① Liquid-LNG inlet
② LNG outlet
③ Refrigeration loop
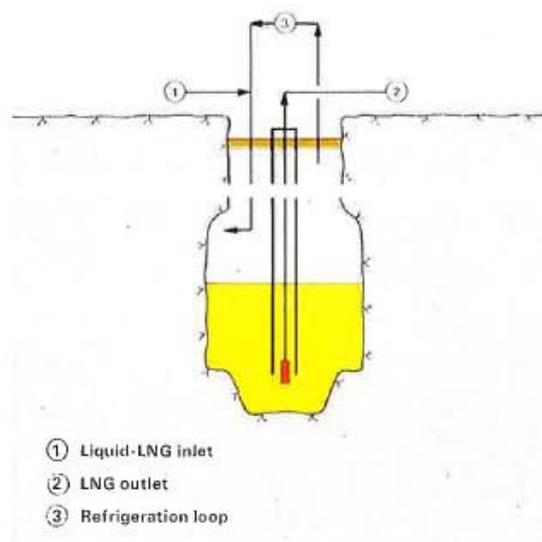
*Figure 5. Principal flow scheme for non- pressurized refrigerated LNG-storage (YIT-brochure, 1984).*

*Table1. Underground LPG-storages in Finland*

| Location | Year completed | Product stored | Pressure MPa | Temp. °C | Capacity 1000 m³ | Rock type |
|----------|----------------|----------------|--------------|----------|------------------|-----------|
| Porvoo U 19 | 1976 | Butane | 0.3 - 0.4 | +8 | 115 | Gneiss |
| U 23 | 1988 | Cas cond. | 0.65 | +8 | 100 | Gneiss |
| U 24 | 1988 | Propane | 1.1 | +8 | 50 | Gneiss |

For a refrigerated LPG cavern the surrounding rock is used as insulation. The vapour pressure is about $0,1 - 0,5$ bar and the corresponding storage temperature is -40 to -30 $^o$C (Broms, L, et.al, 2001). To ensure the tightness in the case of fissures through the frozen zone, a heated water curtain can be installed to limit the extension of the frozen zone and also guarantee sufficient ground water pressure to prevent gas leaks from the frozen zone. Instead water will penetrate into the frozen zone and freeze, thus maintaining the sealing function.

At Oxhaga in Karlshamn, Southeast Sweden, an existing oil storage has been converted to a refrigerated LPG storage facility. The facility has a capacity of 57 000 tons. The work was carried out during the period 1998-1999 and the cavern was ready for use in October 1999. After decontamination, the cavern was cooled down during the construction period to an air temperature of -25 $^o$C by use of permanent and temporary installed cooling equipment. During the air cooling period an unexpected local heaving of the floor occurred. Additional freezing and grouting of rock was required from inside the cavern to stop the heaving, which reached a final extent of 0,5 m. After inspection and approximately 8 months of air-cooling the cavern was finally filled with LPG. The heaving of the rock floor in Karlshamn has never been seen before in a refrigerated cavern.

To maintain the pressure and temperature in the cavern a compressor and re-liquefying installation have to be installed. The cooling capacity has to compensate for the thermal seepage of heat through the rock. The heat inflow of the cavern decreases with time as the surrounding rock is gradually cooled down. The cavern will be sealed by the frozen rock.

A critical phase during the start-up of a refrigerated cavern is to cool the surrounding rock to such an extent, that all inflow of water ceases. This can either be done by direct cooling by spraying of liquid propane into the cavern at start-up of the permanent cooling equipment (operational phase) or by cooling by air during the construction phase. The advantage of air cooling is that the freezing of the rock can be observed and additional actions can be taken to seal any concentrated inflow of water.

The dominating rock in Oxhaga is fine grained, migmatitic gneiss granite. Pegmatite dykes are common in the area. The gneiss has a typical, medium steep foliation and it is normally unaltered. With these properties the geological surrounding of Oxhaga is quite analogical to the bedrock of Southern Finland. The joint frequency was approximately 1-3 per meter and RQD value between 60 and 90, when calculated from drill cores. Joint coatings and fillings consist of

calcite and chlorite. All these properties represent average rock quality. The rock roof is 20-30 m thick, enough for low pressure LPG, but too little for higher pressure of CO2.

Only a few refrigerated caverns had been performed before the Karlshamn conversion, namely in Stenungsund, Sweden (direct cooling) (Jacobson,1977) and in Glomfjord (Goodall&Utheim, 1989) Norway (air cooling), (Niklasson et al., 1999). The air cooling method has been developed in the turn-key project in Glomfjord 1985 and also the heated water curtain system.

## 4.4  CO2 intermediate storage concepts in rock caverns



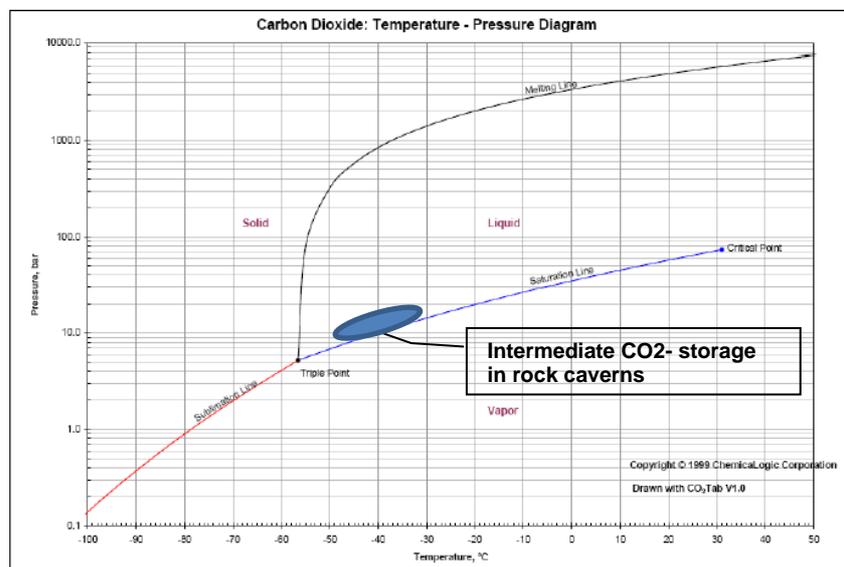*Figure 6. Temperature-pressure conditions of intermediate CO2 storage in rock caverns*

Based on temperature–pressure diagram of CO2 (figure 6) the functional requirements for design of geological intermediate storages in Finnish bedrock conditions can be defined as follows:

T = - (50 - 30) $^{\circ}$C
P = 10 - 20 bar
(>100-200 m below GW-level)
V > about 50 000 m$^3$

# 5  Potential of abandoned mines for CO2 storage

## 5.1  Examples of some abandoned mines

Abandoned mines, which are situated near (logistical maximum 200 km) a CO2 producing plant, have been suggested as possible places to demonstrate underground storage. Several abandoned mines in the vicinity of Porvoo, Pori and Raahe fill this criteria but other criteria will eliminate most of them.

First, historical mines (from 19th century and older) as well as opencast mines are not deep enough (over 100 m). Some potential deep mines are discussed to show different difficulties, which exist if they are modified to CO2 storage. Location of mines in Southern Finland is shown in Figure 7.

*Vihanti* is situated 46 km SE from Raahe. Vihanti was in production from 1951 to 1992 and some 28 milllion tons of ore was quarried. This over 600 m deep mine was closed in 1992. After that the whole mine area has been landscaped, including the access to underground spaces.
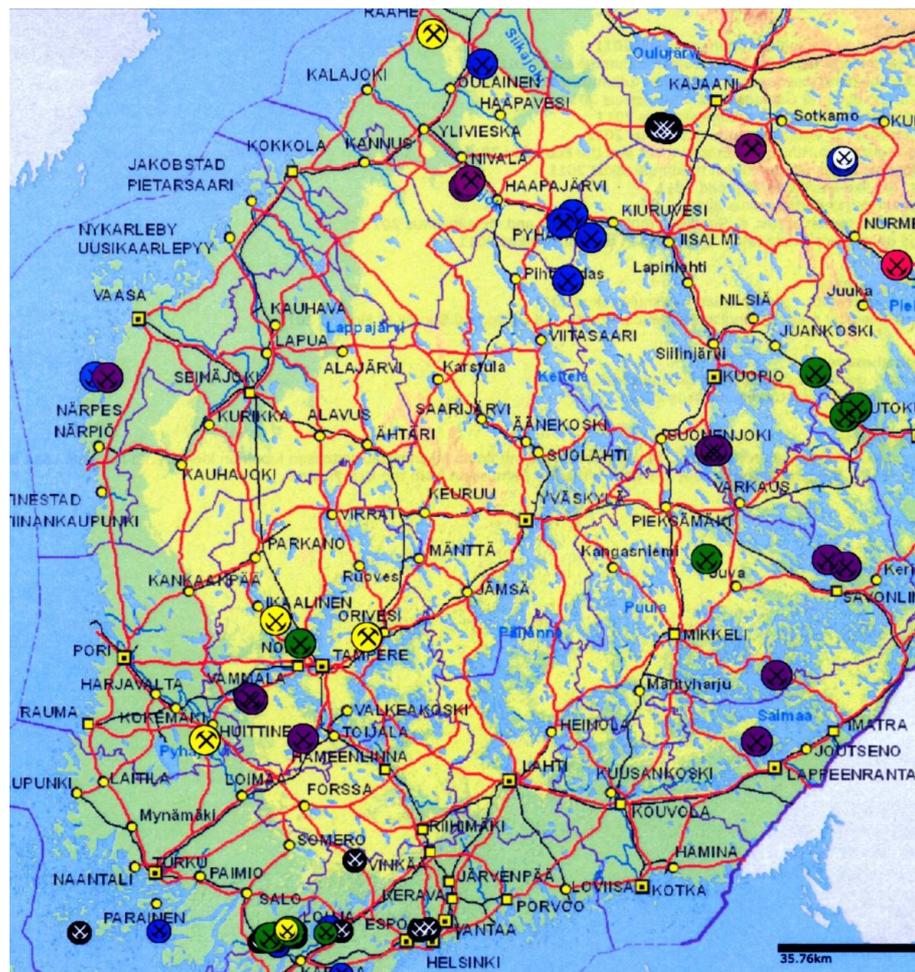


*Figure 7. Mines in Southern Finland. Abandoned mines have hammers upside down; historical mines are shown with small circles. Basemaps: © National Land Survey of Finland, licence no 13/MML/12, Mining registry copyright Ministry of Employment and Economy 2011.*

*Makola* in Nivala municipality is situated about 100 km SSE from Raahe. Production was 410 000 tons ore in years 1941-1954. The mine shaft is 220 m deep, but most underground tunnels are no more than 160 meters from the ground surface. Also thin area is completely landscaped, shaft is closed and the opencast is filled by water. The nearby *Hitura* mine is opened again in 2010.

*Otanmäki* in Vuolijoki municipality, 142 km ESE from Raahe, was Fe-, V- and Ti-ore. About 25 million tons of ore was quarried between years 1953-1985. The main shaft reaches the depth of 550 m. Mine has filled by water and a part of buildings was pulled down. The nearby *Vuorokas* mine was also closed 1985. In 2011 Canadian mining company got interested in the old mine area because of the rare earth elements (REE). This is a "disadvantage" for reuse of old mines: new technique or new minerals/metals can lead to new use of an old mine district.

Stormi in city of Sastamala, 94 km ESE from Pori, was a Ni- Cu-mine in years 1974-1995 and is probably reopened. The original orebody reached 300 m.

Ylöjärvi is situated 110 km E from Pori. It was Cu-mine and its production was about 4 million tons ore in years 1943-1966. Its depth is likely 300 m. Today an institute of defence establishment is operating in the mine area.

Haveri is an old gold mine in the city Ylöjärvi, 98 km E from Pori. It was operating in years 1942-1961, when 1.5 million tons of ore was quarried. Haveri has been again a target of prospecting since 2007. The opencast is a popular diving resort.

Korsnäs is located in the West coast of Finland, 133 km N from Pori. It is an abandoned Pb mine, where almost 7 million tons of ore was produced between years 1958-1972. Today prospectors are interested of rare earth elements of the area.

In Southern Finland mines are uncommon and therefore no abandoned mine lies in the vicinity of Porvoo. Three old and quite shallow mines are found 120 km W from Porvoo, in the area of Kisko, a part of city Salo.

Orijärvi, Aijala and Metsämonttu are old mines, which were producing copper, gold, silver and zinc. Metsämonttu was the only where more than one million tons of ore was quarried. So they are all quite small– and shallow (Aijala > 100 m) mines. Orijärvi was operating in years 1757-1955 and is nowadays a significant cultural heritage nominated by National Board of Antiquities.

Jussarö in the city of Raasepori, is situated in the archipelago, about 125 km WSW from Porvoo. It is a typical banded iron ore and the deposit was mined in years 1961-1967, when the production was only 0.5 million tons. The main part of the deposit and the mine is under the sea, the depth of which is between 10-40 m in the area.

## 5.2 Pros and cons of abandoned mines in CO2 storage

Because of the quite high building cost of underground construction, it would be worthwhile to find ready, unused rock caverns, to demonstrate underground intermediate storage of CCS. Such tunnels exist in abandoned mines, several are also deep-seated enough. Some are ready for study after water has been pumped out. For demonstration only, the size is not so important factor, if the level of stability is acceptable. Unfortunately this kind of data is not available in mining registers and will demand some investigation of the archives of mining companies.

The main weakness of old mines is, that they are not constructed to last long periods. Reinforcement has been used only if necessary and the shape and dimensions of open rooms are not ideal for storage of pressurized gas. The roofs and walls between tunnels can be too thin to stand pressure (without help of surrounding groundwater pressure). The thin walls can also behave in unexpected way when frozen.

The underground quarries can be very high or their span can be long. In any case the mining has essentially changed the tension of the bedrock, which weakens the durability. Mines are very seldom made in good quality bedrock. The ores have often formed in broken and weak bedrock, where jointing and fracturing is more common than in average rocks.

One common disadvantage of old mines is the diversity (incoherency) of underground tunnels and other spaces. It means that it is difficult to seal a room for pressurized carbon dioxide. In Figure 8 a cross-section is shown of (still active) Kutemajärvi mine in the city of Orivesi.

An abandoned mine can become once again a target of interest, when the prices of metals are increasing or new techniques lowers the price of processing. Completely new minerals may have value in the industry, as seen in some cases above.
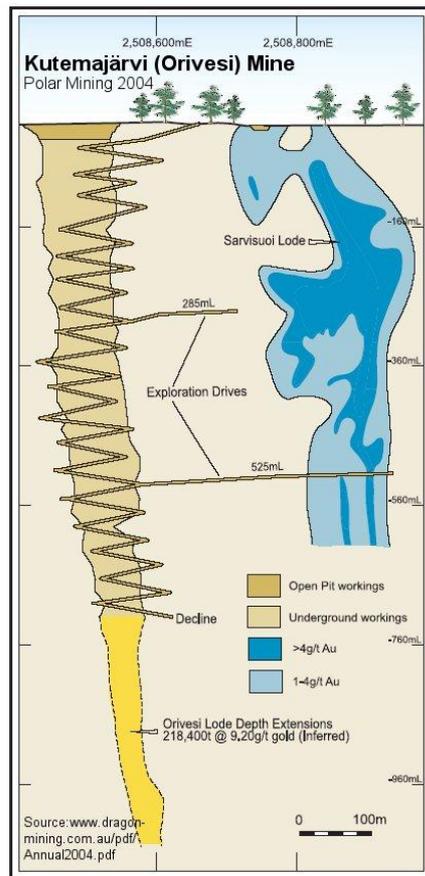
*Figure 8. A simplified cross-section of the deep underground Kutemajärvi mine in Orivesi.*

# 6 Geological environments of potential CCS-cases Porvoo, Pori and Raahe

Preliminary geological data has been collected from three possible CCS-sites. This data includes geological maps (information slightly inconsistent) and other regional studies. Geological and geophysical methods, which could be useful in detailed studies of CCS-sites, are listed and discussed.

## 6.1 Geology of Porvoo

The Kilpilahti site in the city of Porvoo is located on the coast of southern Finland. The bedrock consist of metamorphic (1800-1900 Ma) rocks, at the study site mostly of migmatitic microcline granite and remnants of supracrustal mica gneiss and quartz-feldspar gneiss. Close to the east there is an anorogenic, rapakivi-type Onas granite (ca 1630 Ma). The general bedrock mapping of this area was compiled in 1961 (Laitala, 1984). The abundance of outcrops is great in the Kilpilahti area and therefore field studies are easier to carry out here than on the other two alternative places. The lithology of Kilpilahti area is shown in Figure 9.
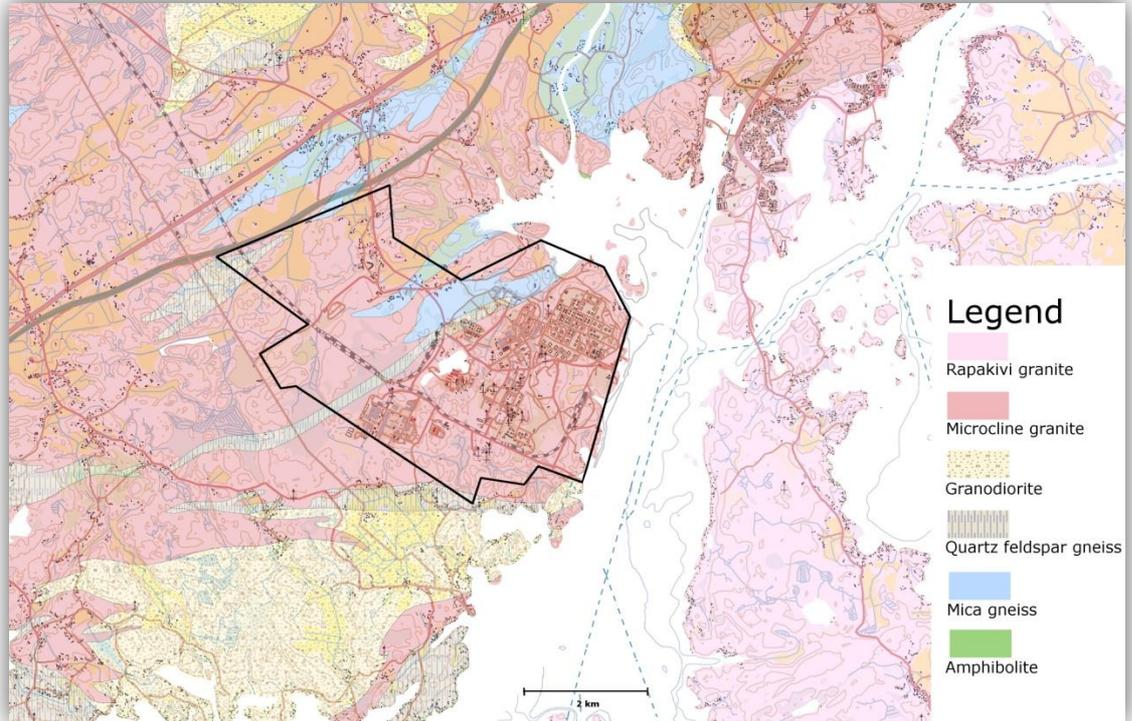
*Figure 9. Lithology of Kilpilahti site, Porvoo. Basemaps: © National Land Survey of Finland, licence no 13/MML/12.*

## 6.2 Geology of Pori

Tahkoluoto site is located at the west coast of Finland, about 26 km northwest from the Pori centre. Tahkoluoto is only two km long island, which limits the study to a small area including the surrounding smaller islands on the east side of Tahkoluoto. On west there is open sea (Pihlaja, Pekka; Kujala, Hannu 2005. Mäntyluoto. 1142). The bedrock consists of metamorphic gneisses, mostly mica gneisses. The synorogenic plutonic rocks are granodioritic in composition. The anorogenic rocks are diabase, which is the main rock of the nearby Reposaari Island, and small rapakivi granite intrusion, which is almost completely below sea level. The sea bottom in west and Mäntyluoto area in the coast, SE from Tahkoluoto, is interpreted as sandstone. Lithology of Tahkoluoto area and its surroundings is shown in Figure 10.
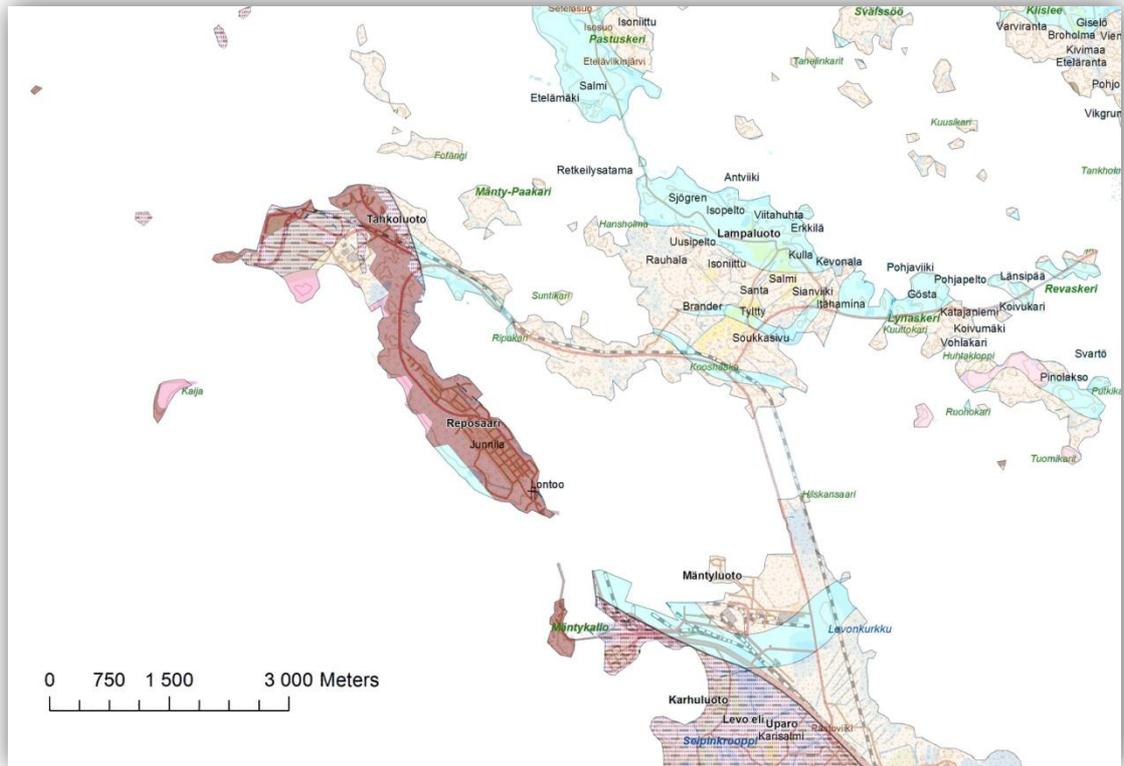
*Figure 10. Lithology of Tahkoluoto site, Pori. Basemaps: © National Land Survey of Finland, licence no 13/MML/12.*

## 6.3 Geology of Raahe

City of Raahe is located on the coast of Bay of Bothnia. The landscape is quite different from the Pori and Porvoo sites. Due to fast land uplift and even topography, outcrops are rare making geological field studies difficult at the Raahe site. Geological mapping was made in 1950s (Nykänen 1959). At the coast zone basic and intermediate metamorphic volcanic rocks prevail. Further east there are also schists and gneisses of sedimentary origin. The synorogenic plutonic rocks are mostly quartz diorites and granodiorites, but right north of the industry area, there is a vast intrusion of migmatitic microcline granite and a smaller gabbro intrusion. Small gabbro and diorite intrusions are common in nearby inlands too.
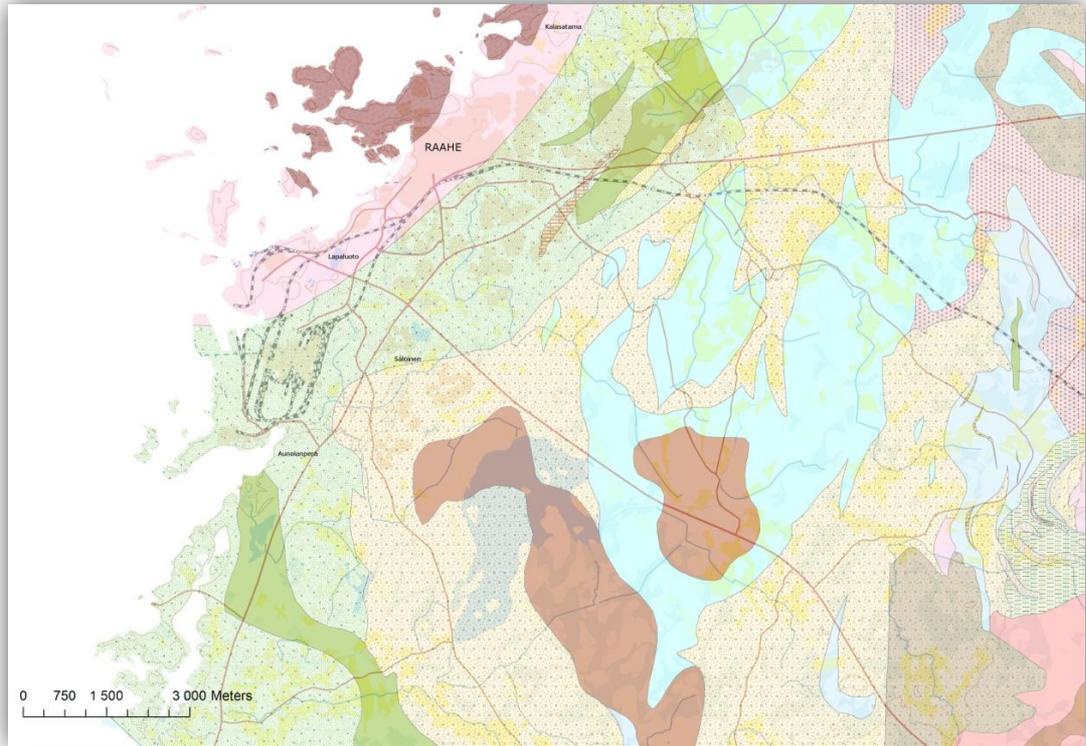
*Figure 11. Lithology of Raahe site. Basemaps: © National Land Survey of Finland, licence no 13/MML/12.*

# 7 Proposal of CCS-case

## 7.1 Proposal of the demonstration plant

The concept of intermediate underground storage of $CO_2$ is being developed based on technological, geological and economic considerations. Suitable sites in the vicinity of $CO_2$ producing plants are selected for more detailed investigations. Assessment of terminal-based logistic solutions under Finnish conditions is further based on this.

Kilpilahti oil industry area has been used as a geological environment for demonstration case development in 2012 work, air photo from area is shown in picture 12. A lot of previous work has been done in Kilpilahti area because of construction of several underground oil storages. These studies include engineering geological investigations and ground water observations, which are reviewed from the perspective of CO2 storage construction.

The principal sketch of the 50 000 m3 underground store is shown in Figure 13.

In figure 13 the principal store consists of two parallel 50 m long caverns and a access tunnel. Both of the caverns are 20 m wide and 25 m high. The top levels of the caverns are situated 160 m under GW-level and the bottom levels 185 m under GW-level. The gradient of the access tunnel (25 m$^2$) is 1:8 and the total length of the tunnel is about 1500 m. However in the case of small underground storage volume, it would be better to excavate only one 100 m long storage cavern.



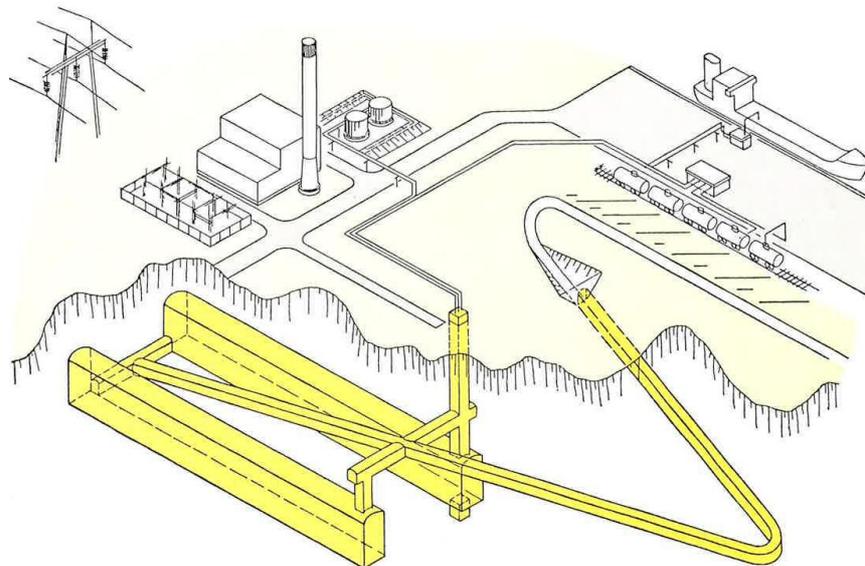*Figure 12. The air photo from Kilpilahti harbour area (Google Earth).*



*Figure 13. The principle layout picture of the intermediate underground CO2-storage (50 000 m$^3$).*

## 7.2 Construction time of the store

Planning, site investigations, offering time etc. 10 - 12 months
The blasting of access tunnel: 1500 m, 50 m/week, about 5 - 6 months
Blasting, supporting and sealing of the caverns both technical construction works inside the store take 9 - 10 months
Initial cooling of the store 5 -7 months by CO2 and by air 3 months extra (Moger J, 2003)

By above mentioned construction deal periods the total construction time of the underground store will be about 2,5 - 3 years.

The chosen cooling method will affect to the initial cooling time of the store. If air cooling system is chosen, it demands 3 months extra time compared to situation, where the initial cooling is made by CO2 product, which will be stored.

### 7.2.1 Construction costs of the underground CO2-store

Underground store: -42 $^o$C, pressure 14 bar
Volume 50 000 m$^3$, 2 parallel caverns A = 500 m2, L = 50 m
(the principle, picture 13)
Access tunnel (1:8): 16 m$^2$, L = 1400 m, 22500 m$^3$
Pipe shaft 140 m, Ø 1,5 m

**Construction costs**

| | |
|---|---:|
| Investigations, design | 250 000 € |
| Project start-up | 500 000 |
| Excavation of access tunnel | 2 700 000 |
| Excavation of storage (blasting , bolting, shotcreting) | 5 000 000 |
| Full drilled shaft | 63 000 |
| Concrete works in storage space | 250 000 |
| Groundwater control | 100 000 |
| Building technical costs | 8 860 000 |
| Fitments and operation | 1 330 000 |
| Total storage | 10 190 000 |
| Extra cost reservation 10 % | 1 020 000 |
| Constructional works together | 11 210 000 |
| Project management (8 %) | 900 000 |
| Reservation for uncertainty 17 % | 1 900 000 |
| **Total cost estimate of storage** | **14 M €** |

### 7.2.2  Cooling effect of underground CO2 - store

Case storage volume 50 000 m3, depth (floor) - 165 m under surface
Cooling rock surface in store:  11 000 m2

**Cooling of store**
Initial cooling effect (first year): 15 W/m2, 165 kW    580 MWh/y
Operational cooling effect (2. year) 10 W/m2, 110 kW    385 MWh/y

**Cooling of CO2/storage charge**
Cooling of 50 000 m3 CO2, (+8,- 42) $^{\circ}$C,    585 MWh/charge
If cooling time 1 week/charge, needed cooling effect is    3,5 MW
Specific cooling capacity of CO2, c = 0,5226 x $10^{-3}$ kWh/kg,K

**Cooling cost of stored CO2**
Initial cooling (First year)    15 000 €
Operational cooling of store (heat losses)    23 000 €/y
CO2 - cooling/charge (50 000 m3)    23 000 €/charge
(Cooling energy price 0,04 €/kWh)

The initial cooling effect (1. year) and the operational cooling effect have been assessed from the earlier modelled theoretical storage case of underground LNG store (Vuopio, 1996).

Properties of saturated liquid Carbon Dioxide - CO2 - density, specific heat capacity, kinematic viscosity, thermal conductivity and Prandtl number can be found in the table 2 below.

*Table2. Density, specific heat capacity, heat conductivity etc. of liquid CO2 in different temperatures. (http://www.engineeringtoolbox.com/carbon-dioxide-d_1000.html ).*

| Temperature - T - ($^{\circ}$C) | Density - $\rho$ - (kg/m$^3$) | Specific Heat Capacity - $c_p$ - ($10^3$ J/kg K) | Thermal Conductivity - k - (W/m K) | Kinematic Viscosity - v - ($10^{-6}$ m$^2$/s) | Prandtl Number - Pr - |
|---|---|---|---|---|---|
| -50 | 1156 | 1.84 | 0.086 | 0.119 | 2.96 |
| -40 | 1118 | 1.88 | 0.101 | 0.118 | 2.46 |
| -30 | 1077 | 1.97 | 0.112 | 0.117 | 2.22 |
| -20 | 1032 | 2.05 | 0.115 | 0.115 | 2.12 |
| -10 | 983 | 2.18 | 0.110 | 0.113 | 2.20 |
| 0 | 927 | 2.47 | 0.105 | 0.108 | 2.38 |
| 10 | 860 | 3.14 | 0.097 | 0.101 | 2.80 |
| 20 | 773 | 5.0 | 0.087 | 0.091 | 4.10 |
| 30 | 598 | 36.4 | 0.070 | 0.080 | 28.7 |

## 7.3 Former studies in Kilpilahti works

The geological characterisation of the Kilpilahti area is aided by extensive previous studies. During the construction of underground storages for oil products several investigations including mapping of bedrock and soil have been carried out. The thickness of quaternary deposits has been measured and the location of main fracture zones has been mapped. A large number of drill core data and samples is available; geophysical parameters in boreholes have been measured, as well as hydraulic conductivity. Studies include also interpretation of in situ stress values and laboratory test of rock compressive strength values. Ground water table monitoring has been made in 55 observation wells since 1971. All these investigations give a remarkable advantage to the design of $CO_2$ storage.

The planning and design of oil storage caverns has followed the schema: first a general site selection based on outcrop mapping. Second a detailed site investigation including a limited number of core drillings, water loss measurements and core sample logging. These are followed by layout recommendation, including a definition of the orientation of the cavern length axis and the minimum acceptable vault level from the hydrological point of view. Estimates of water inflow are important. Recommendations related to reinforcements are given. In Kilpilahti area the length axis of the caverns has been oriented perpendicular to the strike of the schistose components of the migmatite rock mass. Different cavern profiles have all been stable. The two principal reinforcement methods have been bolting and shotcreting.

A summary of all studies was published by Stig Johansson in 1985, and his doctor thesis is the main reference to the following description of the bedrock in Kilpilahti.

### 7.3.1 Bedrock drilling

A small part of the study area of Kilpilahti has been under efficient geological investigation during the 1970s and 1980s. A total of 41 cores have been drilled, with a combined length of more than 3000 m. Individual drill holes varied from 40 to 130 meters in length (Figure 14).

The bedrock of the study area is composed mainly of migmatite, which is a mixture of gneissose rocks, mica gneiss and granite and pegmatite granite (Figure 15). About two thirds of the studied rock mass can be considered as migmatite. Scattered inclusions of mica gneiss, garnet-cordierite gneiss is found in abundance. About one-fifth of the studied rock mass is composed rock called gneiss. Small lenses and dikes of coarse grained granite are common in many locations. About one-fifth of the rock mass is composed of granite and granite pegmatite. Three dikes of amfibolite are found, with width of 0.5 to 2 m. The mean strike of the foliation is 55o (about NE-SW) and the dips are very steep (75-85o) towards SE or vertical.
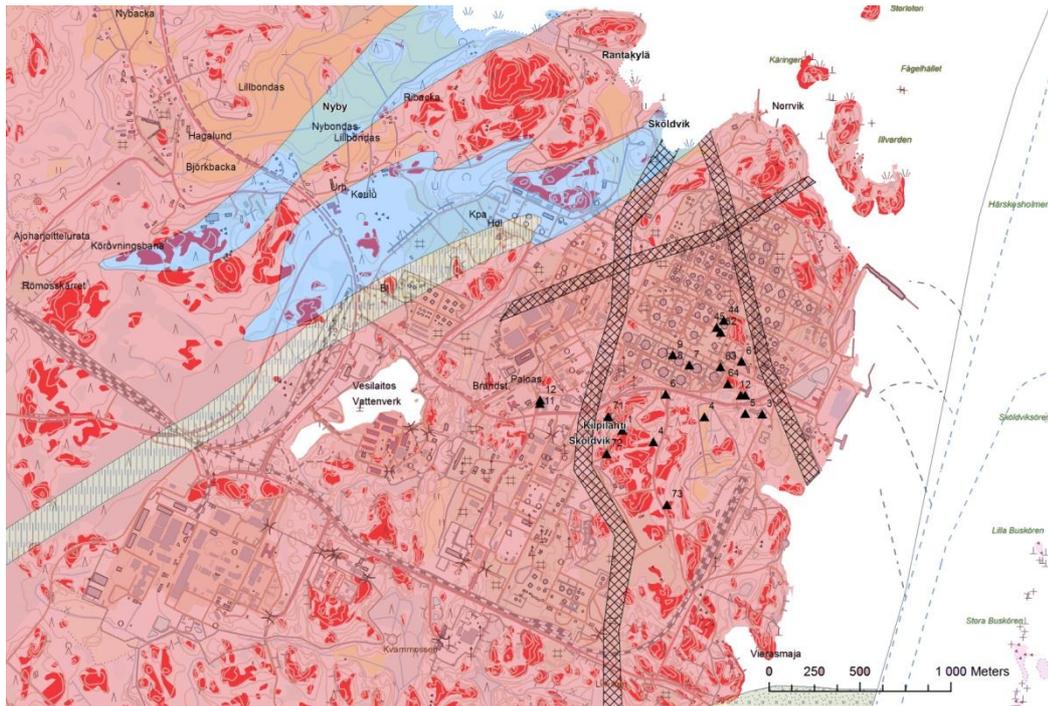
*Figure 14. Kilpilahti area, outcrops have been marked with red color and a part of bedrock drillings with black triangles. The main fracture zones are outlined after Johansson (1985).*

In laboratory tests of rock samples the uniaxial compressive strength values ranged from 100 – 140 MPa (granite), 125 – 275 MPa (gneiss) and 40 – 100 MPA (granite pegmatite). Indirect tensile strength values have been 4 – 19 MPA for all kind of rock types. The rock material strength can be classified as being high to very high.

Three major fracture ("crushed") zones are found in the area (Fig. 14). According to core drillings the completely crushed parts of these zones have a width of 2.9 to 0.8 m at a depth of 25 to 60 m in the bedrock. Disturbed bedrock with slickensided fractures is reaching between 5 and 20 m on both sides of the crushed zones.

Two major sets of joints are almost perpendicular to each other; strikes are 50 – 60o and 130 – 140o. Both are dipping steeply. The horizontal and subhorizontal joint sets are not well developed. Fracture density is 1 – 3 fractures /m in 60 % of core samples, < 1fracture/m about 20 % and 3 – 10 fractures/m about 20 %. The bedrock surface is intensively fractured part of the rock mass and its depth is varying from 5 to over 20 m depending on location. The fracture frequency did not significantly decrease with increasing depth. When the hydraulic characteristics were studied (among others) by means of water loss measurements, the results indicated that the hydraulic conductivity values in the surface parts of the bedrock were clearly higher than in the deeper parts. It can be concluded that the fracture frequency number does not give distinct indications of the hydraulic conductivity of the rock mass in the investigation area.

*Figure 15. Drill core photos of migmatitic rock from Kilpilahti in drill hole SK 11 between 76-81 m depth.*

Johansson (1985) concluded: "In the case of migmatite rock mass at the Porvoo site the stress levels are so low that e.g. rock burst do not develop." Relatively weak horizontal compressive stress field exists, mean values ranging from about 5 MPa to about 16 MPa. Deformations can be considered insignificant from an overall stability point of view. When storage for CO2 will be constructed deeper than the oil storages, somewhat greater stress field can be expected.

## 7.3.2  Ground water conditions in Kilpilahti

The bedrock ground water regime is a dynamic system in which water is kept continuously in motion by force of gravity from areas of recharge to those of discharge (Salmi 1985).

In Kilpilahti several observation wells were drilled in the bedrock and some in the quaternary deposits, mostly clay and till.  Calculated mean variations from long-term observation data indicate that the mean variation has been about 4 m.  Cavern construction can influence to the wells in different ways. Johansson (1985) gives an example where the difference in levels is almost 50 meters over a horizontal distance of only 80 m. Johansson (1985) also concluded that "in this type of rock mass formation can be considered to occur in the form of multiple aquifer system, where the individual aquifers are largely controlled by the presence of almost impermeable zones". In this case the impermeable zone was a shear zone.

Measuring of coastal bedrock wells in 1980's is summarized by Salmi (1985) that the results obtained from the network of drill holes "indicate that the bedrock groundwater table tends to follow the surface topography in the same way as does the groundwater in soil deposits". Variations in the bedrock groundwater table are influenced by changes in the hydrological rhythm and precipitation and also by fluctuations in the level of the nearby sea.

Ground water leaks into oil storage cavern are essential for the safe operation of the facility. An inward hydraulic flow gradient is always maintained in the rock mass. In the case of $CO_2$ storage a continuous water bed is needed to tighten the fractures around the cavern. Average leakage in 22 caverns without water curtain is 7.35 m3/day, which is 0.08 liters/m2 of exposed rock surface. These leaks are notable smaller than leaks in general in Finnish oil storage caverns operating without any type of water curtain system. Johansson (1985) also shows a comparison of different rock types, related to caverns situating elsewhere in Finland. He proves that leakage volume per m2 of exposed rock surface is about ten times higher in granitic rocks as in the migmatitic rock of Kilpilahti area. Rapakivi granite has the most open fractures and leakage rate 30 times that of migmatite. Long-term leak water measurements indicate that the amount of inflow has decreased with time.

### 7.3.3  Future studies

Kilpilahti has several advantages to be a demonstration place for $CO_2$ storage. First of all there is widely studied bedrock, which is proven to be suitable for construction of large caverns. This gives financial benefit to design and reinforcement of a cavern. It is also possible to use some existing access tunnel, which is a remarkable cost in the excavation project. The existing ground water observation wells help control ground water table.

Ground water table is indeed the main trouble in excavation. The storage for $CO_2$ will be constructed notably deeper than oil storages, so it is most important to prevent lowering too much under construction. Some pumping tests and ground water modeling will be needed.

Cooling the storage will result in a frozen zone around the cavern. The behavior of this zone depends on both ground water conditions and rock type. It is also recommended that no fracture zone is situating near the cavern, because of the unexpected behavior during freezing.

# 8 Comparison of intermediate storage economics

This chapter elaborates on the annual costs of both an above- and below-ground intermediate storage unit for CO2 in the scale of the cavern storages, based on available estimates found in literature and the results presented in this study. The summarized fixed and operational costs are presented in Table.

*Table 3. Capital and operational costs of CO2 intermediate storages*

| Type | Unit capacity | Investment(a) | Capital cost(b) | O&M | Reliquefaction cost(c) | Reference |
|------|------|------|------|------|------|------|
| | m³ | M€ | M€/a | M€/a | M€/a | |
| Steel tank | 3000 | 3,150 | 0,224 | 0,032 | 0,007 | Aspelund et al. 2009 |
| Steel tank | 3000 | 7,850 | 0,557 | | 0,007 | Svensson et al. 2004 |
| Cavern | 50000 | 14,000 | 0,993 | | 0,023 | CCSP WP 4.2.1 |
| Cavern | 120000 | 20,521 | 1,456 | | | Svensson et al. 2004 |
| Cavern | 60000 | 55,340 | 3,927 | | | Elsam, KM, Statoil 2003 |

(a) The investment cost are adjusted to currency of year 2013, based on general Euro-area inflation.

(b) Interest rate 5%, economic life 25 years

(c) Assuming electricity cost of 40 €/MWh

## 8.1 Investment costs

An adequate amount of data is not available to determine the scalability of investment costs for cavern storages of various sized. The examples found in literature for cavern investment costs represent the volume of 50 000 to 120 000 m3, and the investment cost are assumed in this study to scale linearly within that range. The results should not be extended to cover cavern storages of lower or higher volumes.

The higher and lower estimates for both tank and cavern storages for CO2 in the range of 50 000 to 120 000 m3 are presented in Figure. The linear interpolate of the current estimate is based on the results of this study.
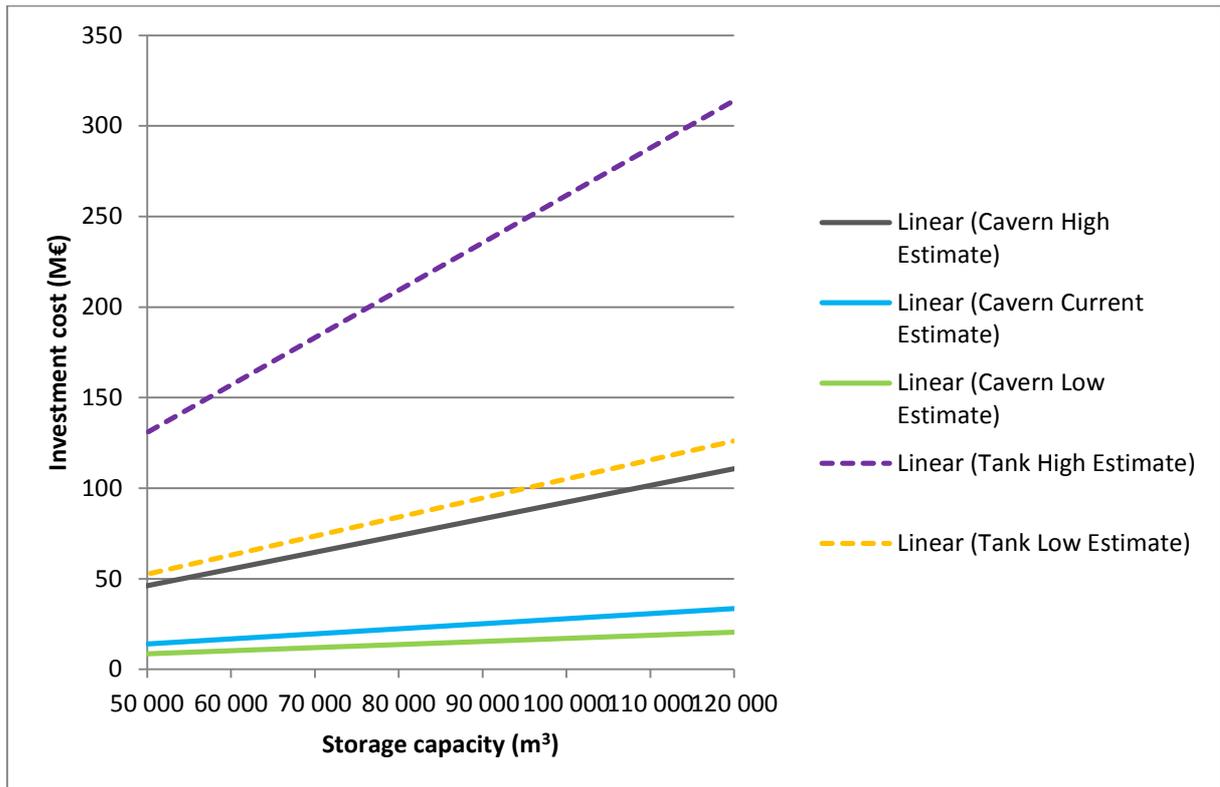
*Figure 16. Comparison between investment cost of storage caverns and steel tanks, as found in literature. Refer to the references in Table.*

## 8.2  Operation and maintenance

Assuming an interest rate of 5 % and an economic life of 25 years, the capital cost of a single 3 000 m3 steel tank equals from 0,224 M€/a to 0,557 M€/a (based on Aspelund et al. 2009 & Svensson et al. 2004). Aspelund et al. (2009) assumed an operation and maintenance costs amounting to 1% of the investment, resulting in this case from 0,0315 M€/a to 0,0785 M€/a.  The operation and maintenance costs, represent therefore roughly 14% of the annual fixed costs of an above ground $CO_2$ intermediate storage when cost related to liquefaction process are neglected.

When the reliquefaction cost resulting from the operation of a single 3 000 m3 tank unit are taken into account and the operation and maintenance cost are neglected, the annual cost of the unit amounts to 0,231 M€/a to 0,564 M€/a. The reliquefaction costs, equalling 0,007 M€/a per a 3 000 m3 tank, represent roughly 1-3% of the annual cost. On a rock cavern of a size of 50 000 m3, the annual reliquefaction cost 0,023 M€/a equals some 2 % of the annual cost without operation and maintenance costs.

# 9 Conclusions

The results underpin the commonly assumed economic benefits from investing into caverns instead of modular on-ground tanks for large, over 50 000 m3 intermediate storages for CO2. The economic difference between the storage modes is a result of significantly lower investment cost per storage volume of a cavern compared to steel tanks. The operational and maintenance costs can be assumed to represent only a minor share of the annual cost of a storage facility. The annual costs from reliquefaction of boil-off CO2 from both cavern and tank storages were of the same order of magnitude compared to the investment costs. However, the subject does not appear often in the scientific literature, and the available data does not provide basis for a robust analysis. The risk of error or misjudgement remains high.

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