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CLEEN - CCS Task 4.21
CO2 - Terminals and Intermediate storage

Final Report 2013

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Carbon Capture and Storage Program

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Key words: CO2 - terminals and transport, intermediate storage, underground storage, geology, construction, economy

Abstract

This document is intended as an internal working paper of CCS WP 4.2.1 including periods FP1-FP3. 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 a potential environment for 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 larger intermediate storages for CO2. In the light of the results the rock caverns can become more economical compared to tank farm storages at capacities considerably under the 50 000 m3 range reported by Elsam, K&M, and Statoil (2004). 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.

The research and development work in CCS WP 4.2.1 was carried out in cooperation by VTT Technical Research Centre of Finland and Geological Survey of Finland (GTK), Fortum Oyj and Neste Oil Oyj. This report has been written by partners so, that VTT has coordinated the work, analysed the research results and written the most part of the report. GTK has written the follow geological parts of the report: Chapter 5*: Potential of abandoned mines for CO2 storage*, Chapter 6*: Geological environments of potential CCS-cases Porvoo, Pori and Raahe*, and Chapter 7.1*: Site selection for underground intermediate CO2-storage – a geological point of view.*

Helsinki, February 2014

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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 (**Error! Reference source not found.**).

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 **Error! Reference source not found.**.
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

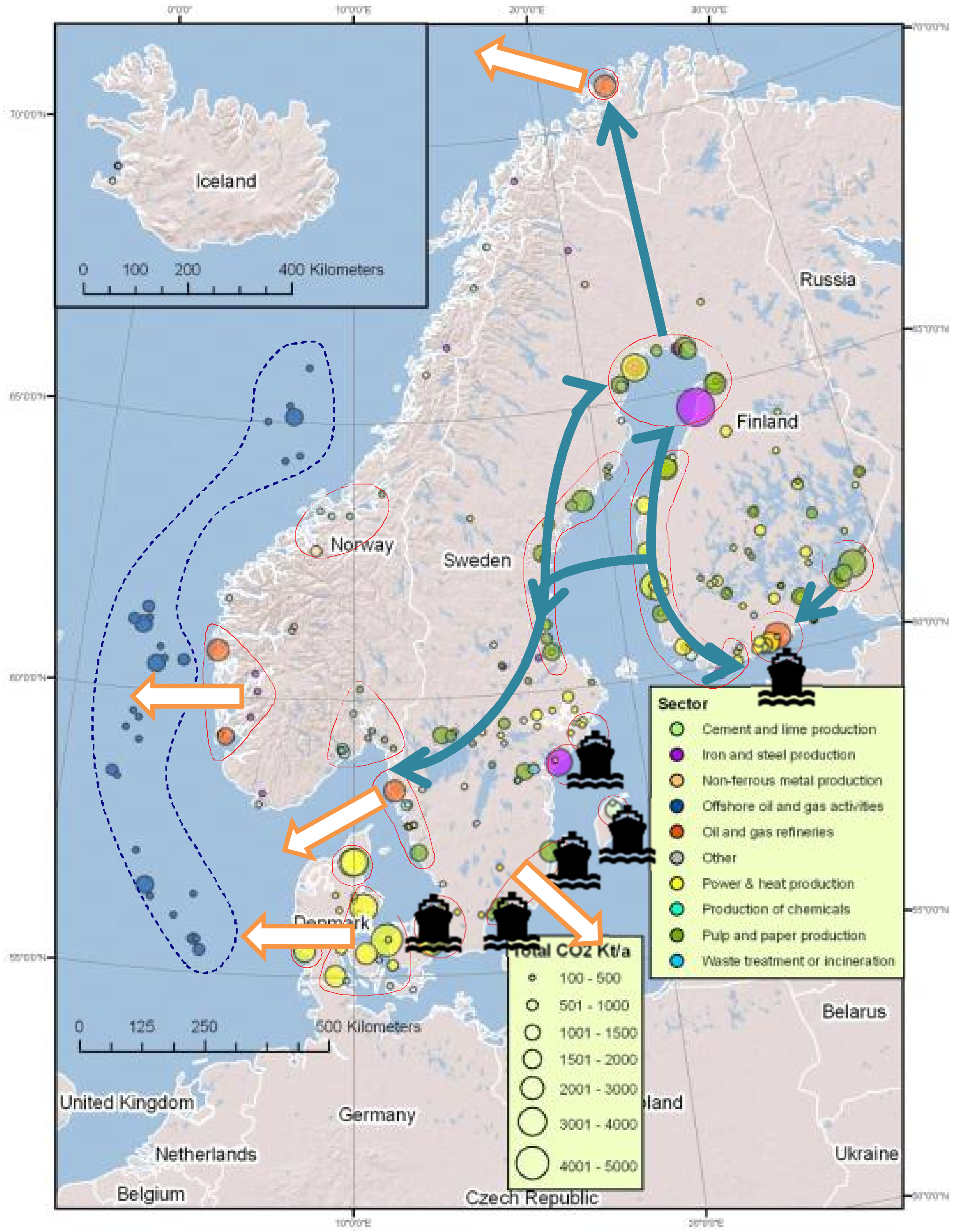
Cost efficient logistics would be required to enable CO2 capture from Finnish point sources for the purposes of geological storage. The transport distances would be significant, as no domestic storage capacity is available. Moreover, suitable geological formations are unlikely to be discovered in the 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 CO2 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. In 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)).



🚢 Exporting terminal: an intermediate storage

↑ CO_2 pipeline

⇧ Forwarding terminal: an intermediate storage and a connection to a sequestration site

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 an 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.

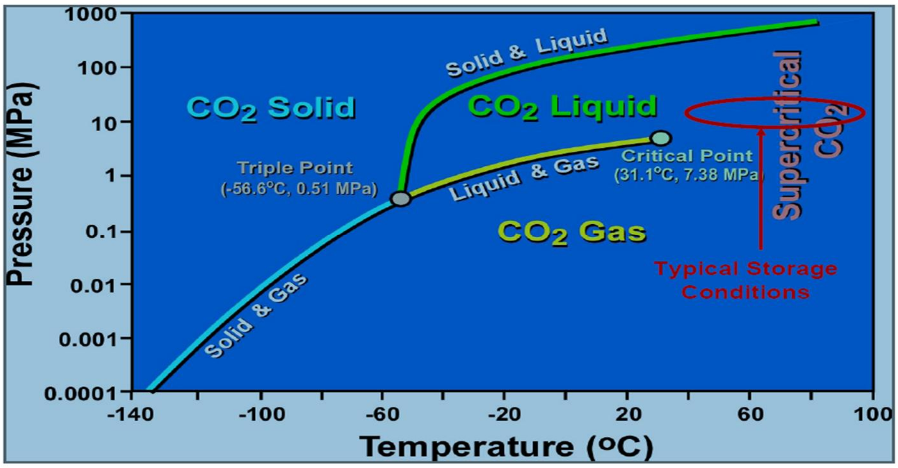


Figure 2 a

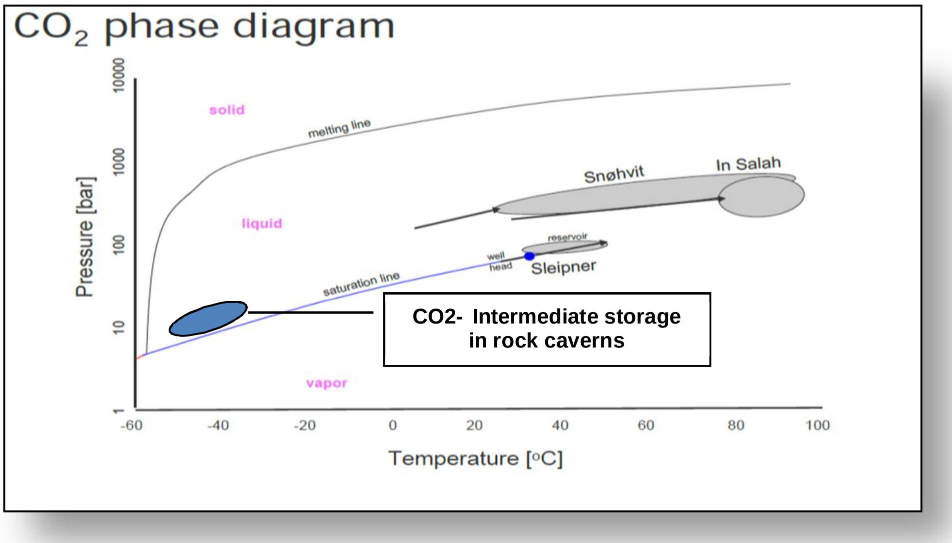


Figure 2 b

Figure 2. CO2-phase diagram 2a) 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].

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 (Figure 3) 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.

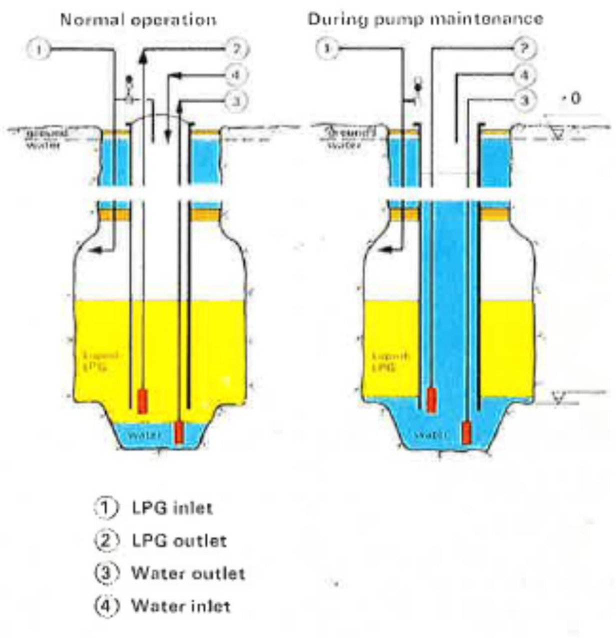


Figure 3. Principal flow scheme for pressurized LPG-storage (YIT-brochure, 1984).

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 ^{o}C (Neste Engineering 1986). A schematic picture of pressurized LPG storage is shown in Figure 4.

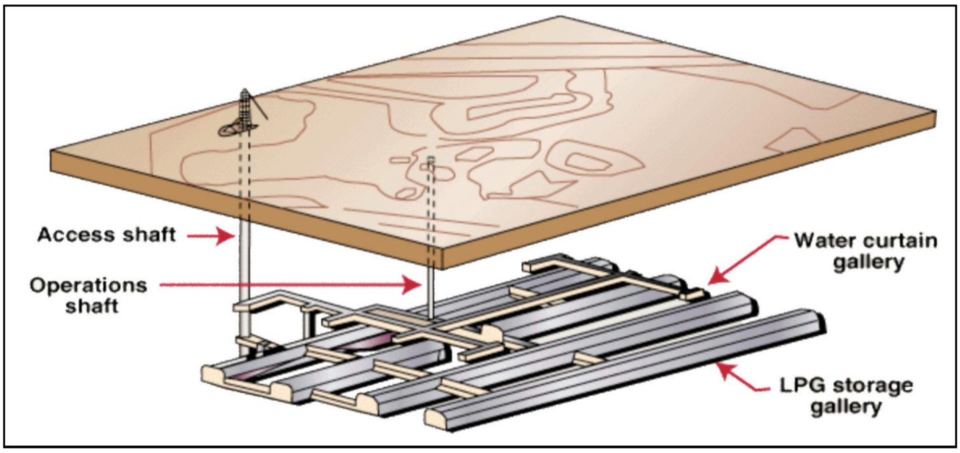


Figure 4. A schematic view LPG storage locating in Sydney. The capacity of storage is 130 000 m^3/65 000 tons. The dimensions of storage tunnels are 14 m/11 m/230 m (B/H/L) and the tunnels for water curtain are 4 meters in breadth and 3.5 m high (The Allen Consulting Group 2009).

4.3 Refrigerated non-pressurized gas cavern storage

Non-pressurized gas storage (Figure 5) 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.

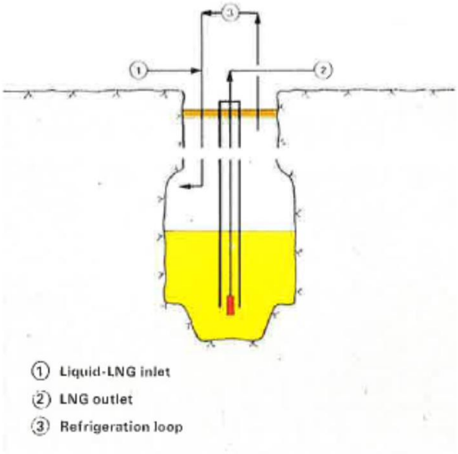


Figure 5. Principal flow scheme for non- pressurized refrigerated LNG-storage (YIT-brochure, 1984).

Table 1. Underground LPG-storages in Finland

Location	Year completed	Product stored	Pressure MPa	Temp. ^{o}C	Capacity 1000 m^3	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

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) °C
P = 10 - 20 bar
(>100-200 m below GW-level)
V > about 50 000 m^3

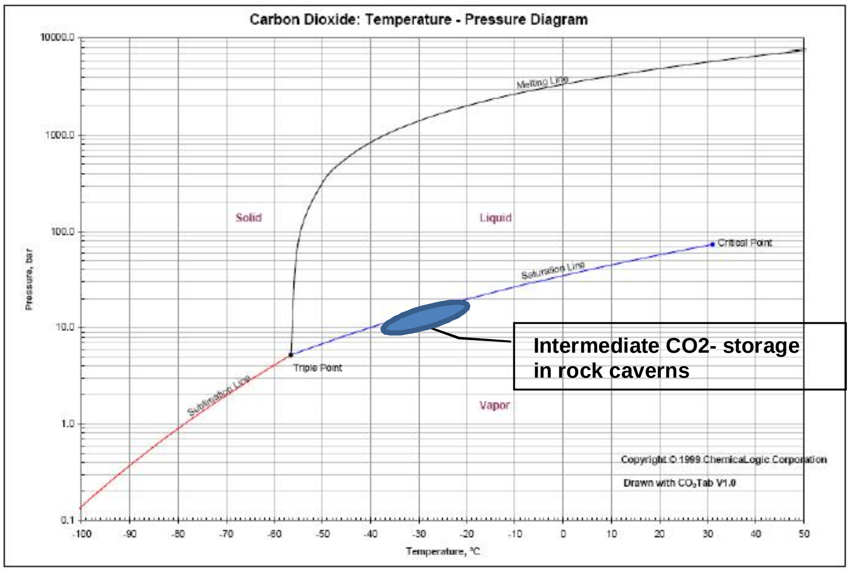


Figure 6. Temperature-pressure conditions of intermediate CO_2- storage in rock caverns

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.

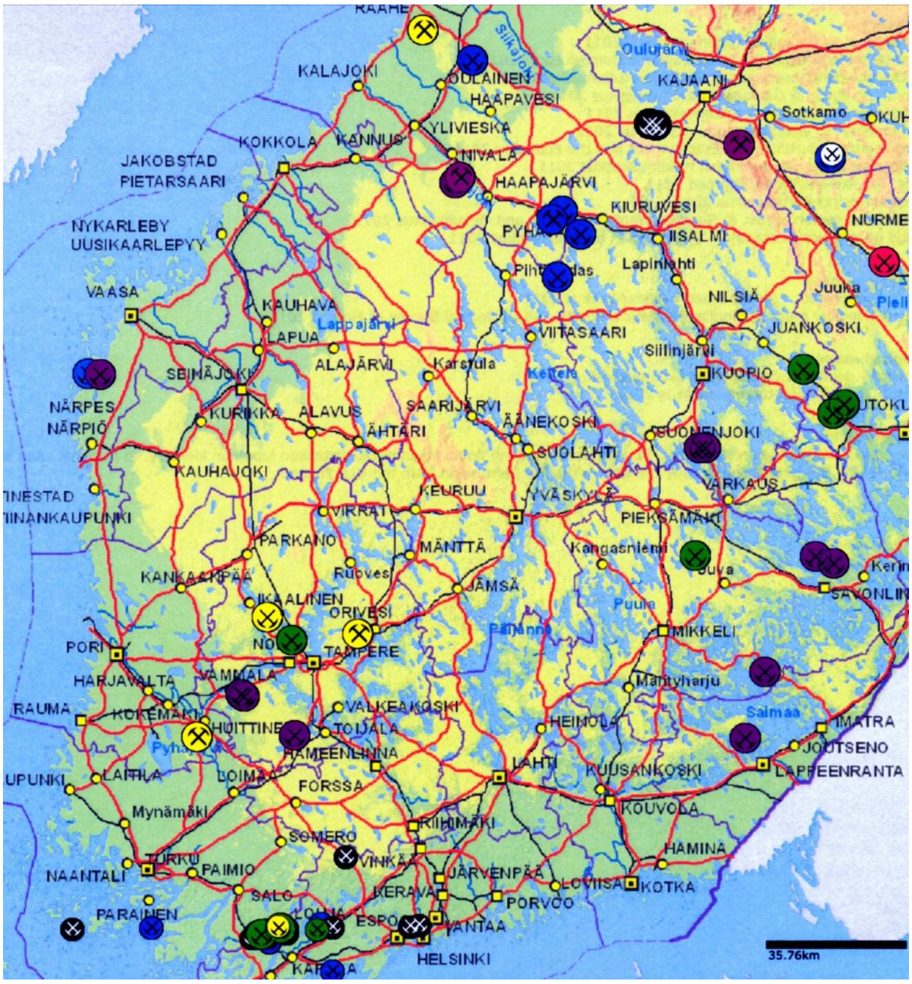


Figure 7. Mines in Southern Finland. Abandoned mines have hammers upside down; historical mines are shown with small circles. Basemaps: © National Land Survey of Finland, licence no 13/MML/12, Mining registry copyright Ministry of Employment and Economy 2011.

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

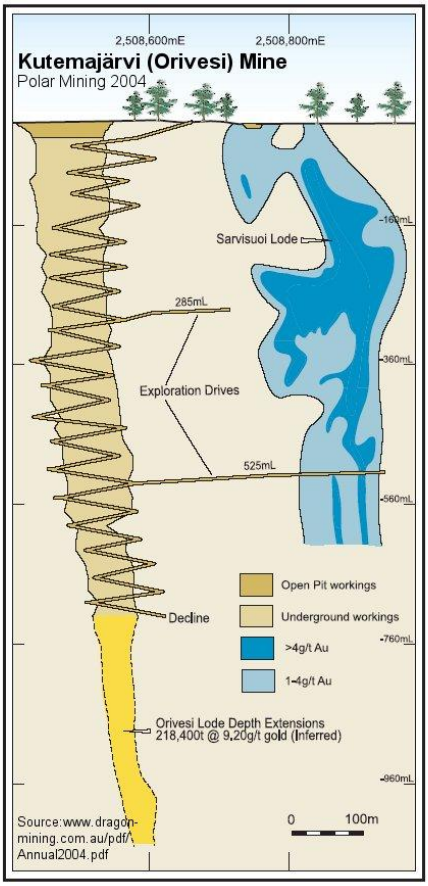
Because of the quite high building cost of underground construction, it would be worthwhile to find ready, unused rock caverns, to demonstrate underground intermediate storage of CCS. Such tunnels exist in abandoned mines, several are also deep-seated enough. Some are ready for study after water has 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.



Source:www.dragon-mining.com.au/pdf/Annual2004.pdf

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.

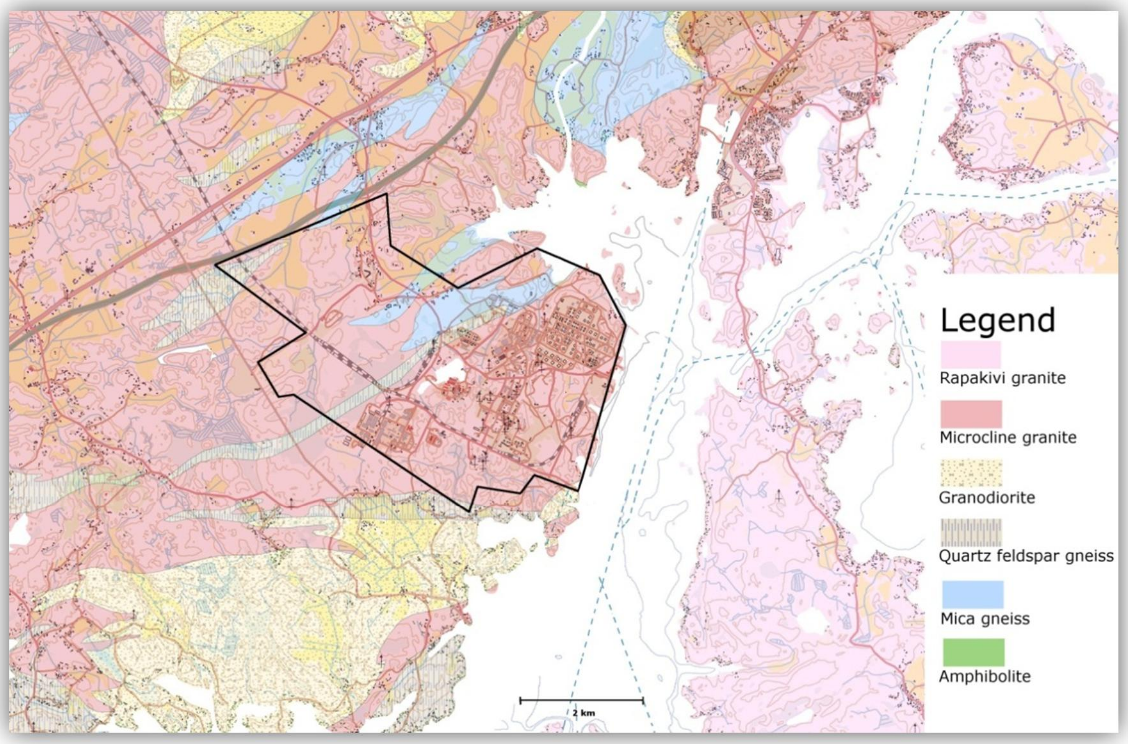


Figure 9. Lithology of Kilpilahti site, Porvoo. Basemaps: © National Land Survey of Finland, licence no 13/MML/12.

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.

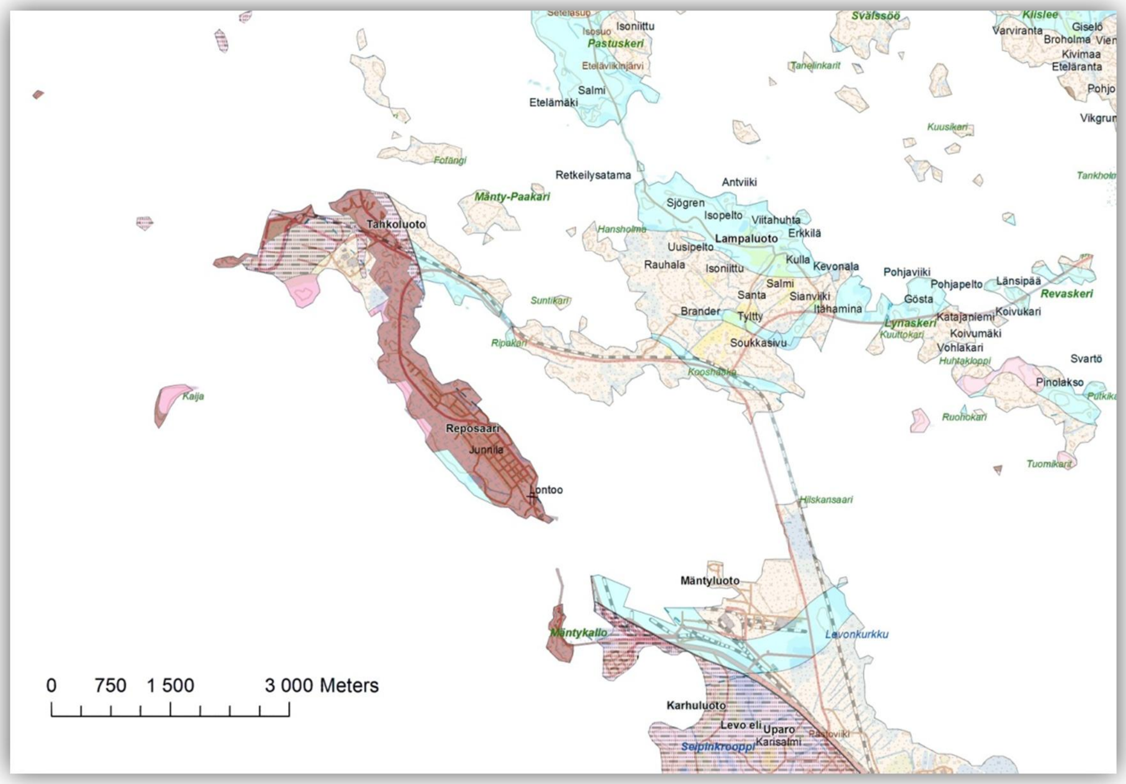


Figure 10. Lithology of Tahkoluoto site, Pori. Basemaps: © National Land Survey of Finland, licence no 13/MML/12.

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.

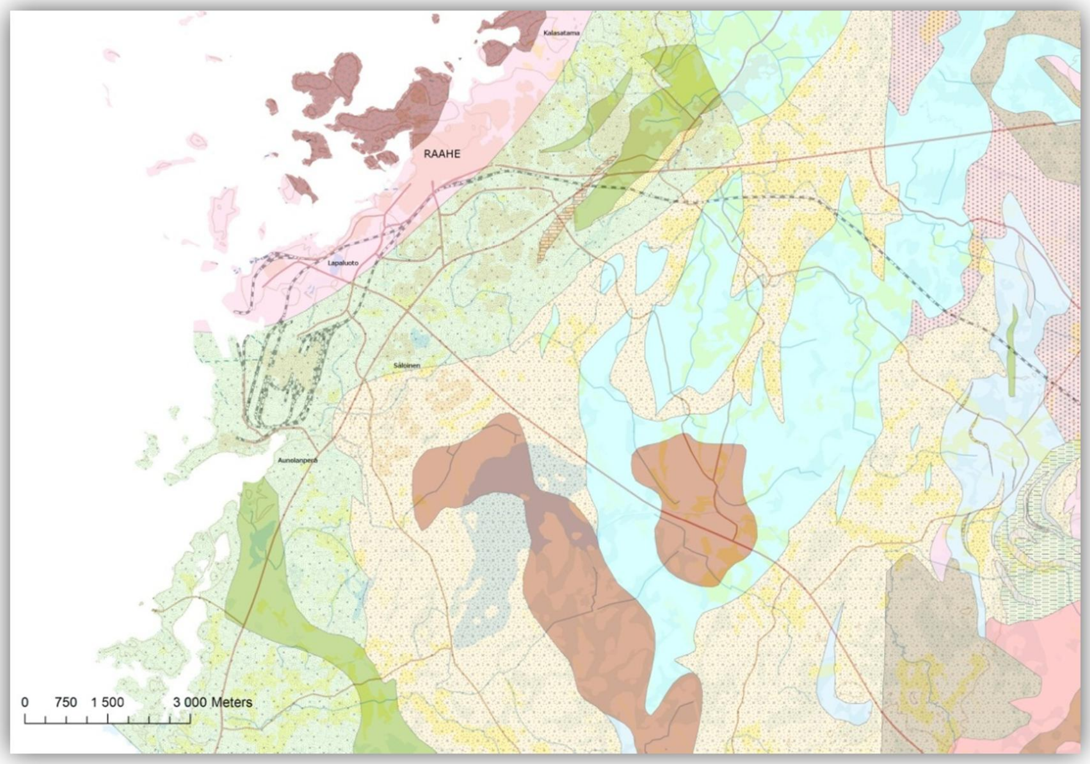


Figure 11. Lithology of Raahe site. Basemaps: © National Land Survey of Finland, licence no 13/MML/12.

7 Proposal of CCS-case

7.1 Site selection for underground intermediate CO2-storage – a geological point of view

7.1.1 Basis of site selection

This description with recommendations to site selection for geological intermediate storage for carbon dioxide is based on the site selection procedure for nuclear waste. Many factors are the same, but many requirements are lower, as the gas storage is thought to be in controlled use as any other industrial plant. The site selection process for nuclear waste is described for example by McEwen and Äikäs (2000).

Logistically storage of carbon dioxide will be situated near some industrial plant, where production of CO2 is high. And further, a coastal plant will be favourable as sea transport to the final storage site is the most likely alternative. An industrial area has a lot of benefits, such as simple permission procedure for construction licence; ready to use roads and possibly even stacking area for rock waste and sedimentation basin for cleaning out pumped ground water. On an industrial site the availability of labour force is good and transport paths are in order. The public acceptance and land ownership are also important considerations.

In Finland several big producers of carbon dioxide are situated along the coast and therefore it will be interesting to compare the geological properties of those sites and choose geologically most suitable site for the first intermediate CO2-storage. The benefits of geological storage, compared to traditional steel tanks, are discussed elsewhere.

The main geological criterion for storage is the constructivity of the bedrock. Fracture zones should be avoided as well as abnormally high rock stress. Stable ground water conditions are also advantageous. The depth of storage, about 150 meters, means that some geophysical investigations are necessary to obtain the properties of the bedrock.

The usually low topography in coastal regions of Finland has no great effect on the hydraulic gradient at the depth of storage. The main significance of topography is how it projects the possible faulting or fracturing of the bedrock.

The type and frequency of fractures are important factors to the ground water flow. An even water "curtain" that surrounds the storage is an advantage. During the operation a frozen zone will form around the storage, where water in conductive fractures freezes and thereby seals the storage.

The Finnish bedrock is tectonically stable; seismic activity is very low and bedrock movements, land uplift for example, are associated with old fracture zones. The glacial isostatic land uplift is several millimetres per year in the Gulf of Bothnia, but this would not be preventing factor to the construction of underground storage facilities.

Rock type and homogeneity are not remarkable aspects as all Finnish rock types have adequate strength for construction.

Summary: before starting a building project it is necessary to find out fracture zones, both vertical and horizontal, of the area as well as the prevailing stress field. The long axis of storage tunnel should be aimed parallel to the main horizontal stress direction. In the next chapter the procedures and tools for site selection are explained in more detail.

7.1.2 Methods for site selection

At first stage from 3 to 6 industrial sites are chosen by their technical properties. This evaluation should be based on the logistic properties and that enough space for buildings on ground and storage cavern is available.

Then a preliminary geological survey is carried out with bedrock and fracture mapping; lithological units and local deformation is explained. At this phase it is possible make estimation which sites are more favourable for the next surveys. For example a thick and extensive soil cover can hinder further investigation.

In second phase the area is examined with geophysical methods to find out possible fracture zones deep in the bedrock. Ground penetrating radar (Figure 12) is useful to measure thickness of soil and find out the quality of bedrock surface. More precise data of fracture zones is possible to get with seismic refraction survey and resistivity measurements. These methods can easily reach the depth of storage. If any site contains remarkable fracture zones, thickness > 1 m and length tens of meters, it should be withdrawn from further site studies after geophysical measurements.

Figure 12. Ground penetrating radar. Photo Jari Väätäinen, Geological Survey of Finland.

In next phase one deep and several/few shallow borehole will be drilled. The aim of the deep one is to study lithology, structure, fracturing and weathering in the rock mass and especially in the depth of storage. The deep borehole allows hydrological monitoring, stress tests and, if needed, studies of ground water chemistry. Hydraulic heads are measured from shallow boreholes and this data will be connected to precipitation.

The site selection for nuclear waste included several deep boreholes and very sophisticated geophysical measurements in and between boreholes (McEwen and Äikäs 2000). These included different seismic and electric methods as well as borehole radar and scanner logging. In situ horizontal stress was measured using hydraulic fracturing with double-packer method.

During the drilling it is recommended to make water loss tests with single packer method, measure returning drilling fluid and take so much oriented core samples as possible. Core samples are used to study mineralogy, structure, fracturing and rock mechanical properties. Only core samples make quantitative rock mass description (Q-value) possible. This is a base for storage design and excavation planning.

The preliminary geological survey can be run in one to two weeks per site, but geophysical investigations in phase two take more time, possibly one week on field (two persons) and two man-weeks modelling in office. In phase three drilling and geophysical measuring in the boreholes would last one month with personnel of two – three people and modelling after that about four man-weeks. Hydraulic head measuring should be made weekly during one year.

When the most suitable site has been chosen, some more drilling is necessary to get detailed information for excavation of the storage.

7.1.3 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.

7.1.4 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 13).

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.

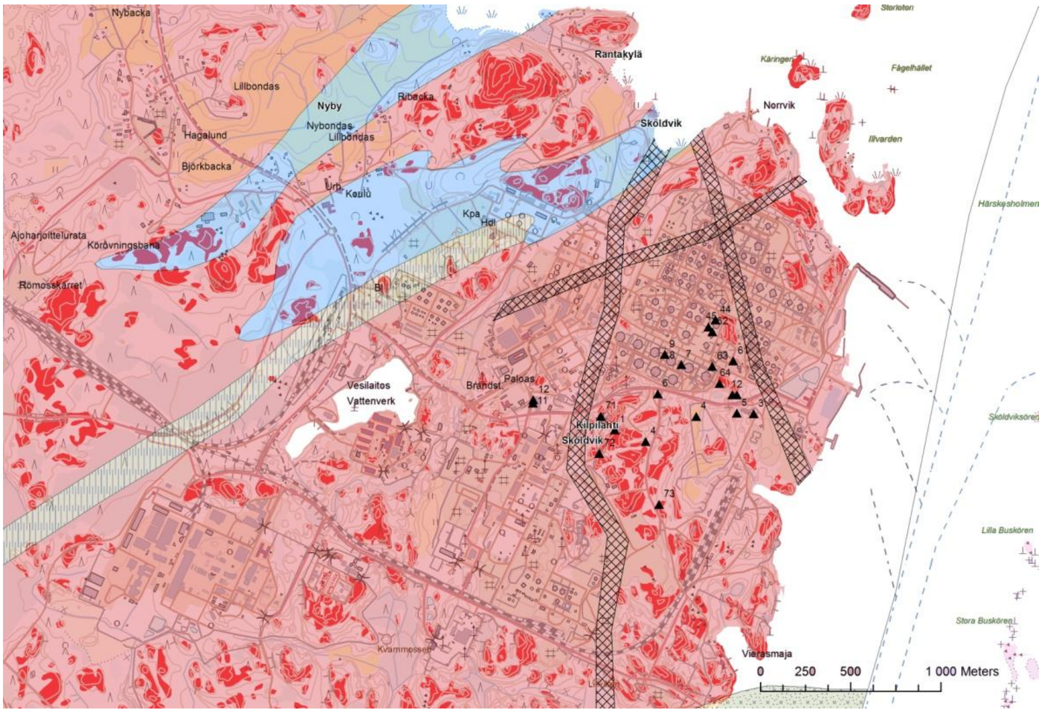


Figure 13. Kilpilahti area, outcrops have been marked with red color and a part of bedrock drillings with black triangles. The main fracture zones are outlined after Johansson (1985).

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 (Figure 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 sub horizontal 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 14. 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.

7.1.5 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 CO2 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 m^3/day, which is 0.08 liters/m^2 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 m^2 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.

7.1.6 Future studies

Kilpilahti has several advantages to be a demonstration place for CO2 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 CO2 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.

7.2 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 Figure 15. 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.

Figure 15. The air photo from Kilpilahti harbour area (Google Earth).

7.2.1 Case study of 50 000 m3 underground demonstration plant

The principal sketch of the 50 000 m^3 underground store is shown in Figure 16.

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.

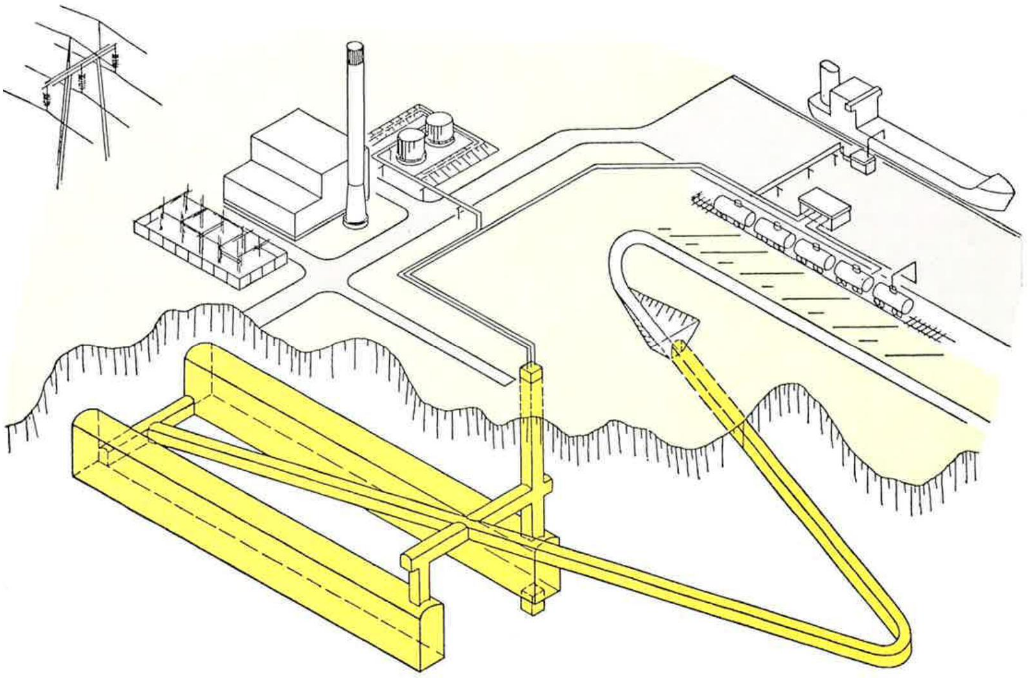


Figure 16. The principle layout picture of the intermediate underground CO2-storage (50 000 m^3).

7.2.2 Construction schedule 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.

7.2.3 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 €**

7.2.4 Cooling effect and cooling cost of underground CO2 – store

VTT has modelled and guided the heating and cooling needs of underground spaces in several research projects during last 40 years. For instance the cooling effect and freezing zones around the underground (NLG) gas storage has been investigated in different modelling works. The needed cooling effect of LNG-storage is very similar with the cooled CO_2-storage.

In Figure 17 has been shown the needed cooling effect of a large underground NLG-store, which operating temperature is – 40 ^{o}C (Vuopio, 1996). The span width of the storage cavern has been 35 m and the height 60 m. In his case the frozen rock zone around the store is modelled to be 30-40 m. Depending on, how long time period (6 months, 12 months) can be used for initial cooling of the store before the storage operation is starting, the constant cooling effect can be dimensioned by a little different way. If we choose in Figure14 initial cooling period 12 month, we can choose for initial cooling effect 15-20 W/rock-m^2 and then for the constant cooling effect about 10 W/rock surface-m^2. In follow cooling cost calculations has been used just 15 W/rock-m^2 for initial cooling effect and 10 W/m^2 for operational cooling of the underground CO_2-store cooled to – 40 ^{o}C.

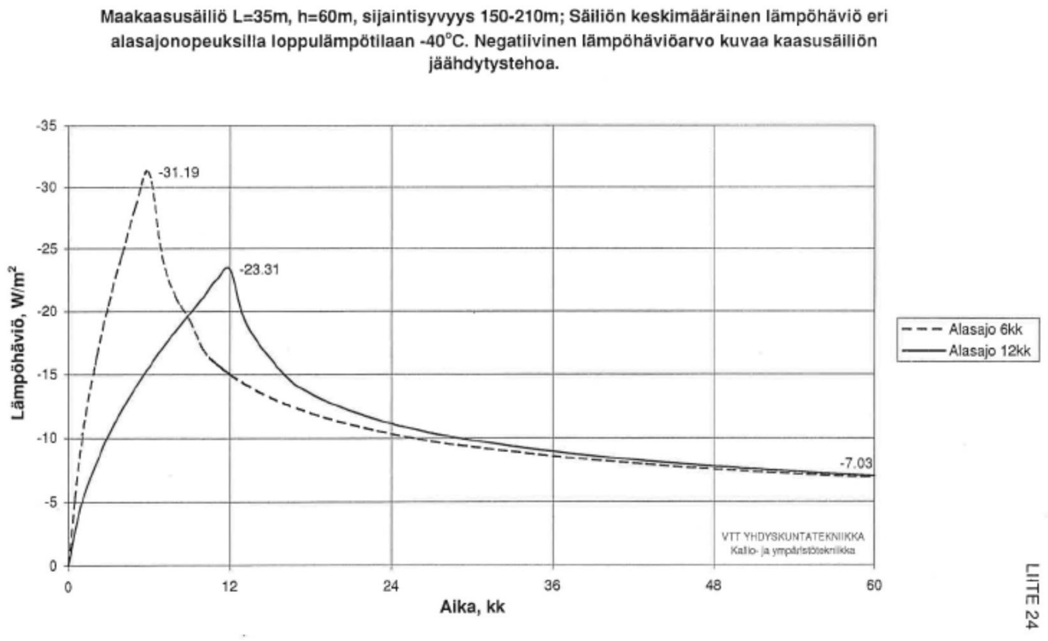


Figure 17. Modelled cooling effects of underground LNG-store, cooled to – 40 °C (Vuopio, 1996).

In follow cooling cost calculations has been used just 15 W/rock-m^2 for initial cooling effect and 10 W/m^2 for operational cooling of the underground CO_2-store cooled to – 40 °C.

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

Cooling of store

Cooling by electricity sourced compressors, COP = 2,5	Electricity consumption
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) °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	

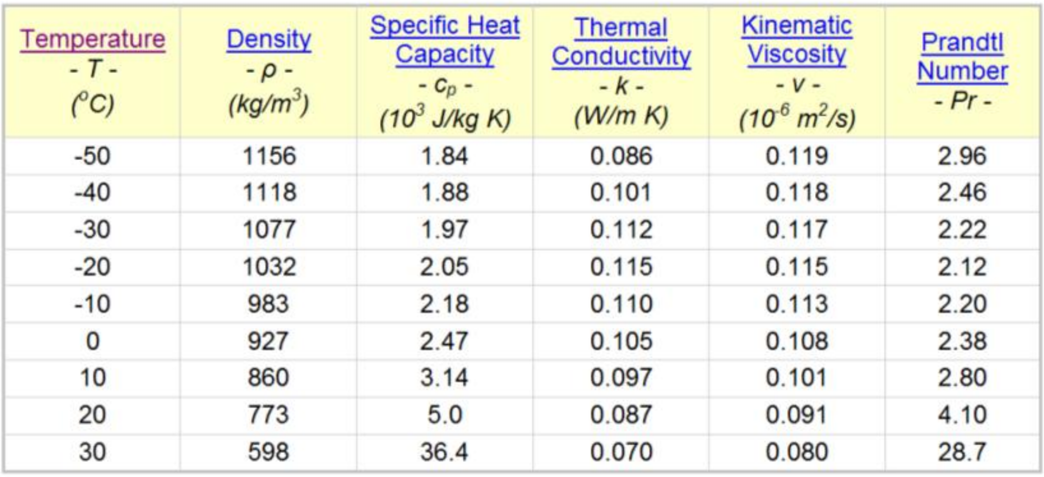
Cooling cost of stored CO2

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 40 €/MWh)	

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.

Table 2. Density, specific heat capacity, heat conductivity etc. of liquid CO2 in different temperatures. (http://www.engineeringtoolbox.com/carbon-dioxide-d_1000.html).



Temperature - T - (^oC)	Density - ρ - (kg/m^3)	Specific Heat Capacity - c_p - (10^3 $J/kg\ K$)	Thermal Conductivity - k - ($W/m\ K$)	Kinematic Viscosity - ν - (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

8 Comparison of intermediate storage economics

This chapter elaborates on the annual costs of both an above- and below-ground intermediate storage unit for CO_2 in the scale of the cavern storages, based on available estimates found in literature and the results presented in this CCSP WP4 study. The summarized fixed and operational costs are presented in Table 3. The examples found in literature for cavern investment costs represent the volumes of 60 000 to 120 000 m^3. Additionally, investment cost estimates have been done within the CCSP WP4 task for a cavern storage of 50 000 m^3.

The references in literature mentioning investment costs for intermediate gas storage facilities suitable for CO_2 are few. Therefore, any straightforward statistical analysis of the data would not deliver useful results on estimated cost for an intermediate storage facility as a function of storage volume. Here, an alternative approach is applied to the cost data in order to derive at least crude linear relations between alternative storage technologies, volumes and investment costs. The goal is to both compare the reported cost between the storage technology options and to present best available equations for use in cost estimations of CO_2 intermediate storages.

Table 3: Summary of capital and operational costs of CO_2 intermediate storages. Based on Aspelund et al. 2009, Svensson et al. 2004, Decarre et al. 2010, Elsam, KM & Statoil 2003 and CCSP WP4 results.

Type	Unit capacity m^3	Investment [(a)] M€	Capital cost[(b)] M€/a	O&M M€/a	Reliquefaction cost[(c)] M€/a	Reference
Tank farm	19 500	18,700	1,327	0,187	0,047	Aspelund *et al*. 2009
Steel tank	3 000	8,010	0,568		0,007	Svensson *et al*. 2004
Tank farm	63 000	117,116	7,619		0,150	Decarre *et al*. 2010
Cavern	50 000	14,000	0,993		0,023	CCSP WP 4.2.1
Cavern	120 000	20,521	1,456			Svensson *et al*. 2004
Cavern	60 000	55,340	3,927			Elsam, KM, Statoil 2003

(a) The investment costs 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

Above-ground CO_2 intermediate storages consist of a number of pressurized and refrigerated steel tanks. Studies by Elsam, KM and Statoil (2003) and Svensson *et al.* (2004) propose a unit size of 3 000 m^3 for a single tank. Decarre *et al.* (2010) base their cost estimates on somewhat larger unit sizes. Due to the modular structure of tank farms, the investment cost is assumed to grow linearly from zero as the volume of the storage is increased. Therefore, the cost equation for an above-ground intermediate storage would be stated by the following equation 1:

Investment cost [M€] = b * total storage volume [m^3] (1)

Using the above assumption, the upper and lower estimates for tank farm investment costs are easily found by comparing the single cost data points, as shown in Figure 18. Unlike the tank farm storages, the cavern storages can be assumed to have lower investment costs per storage volume at higher capacities that at lower capacities. The caverns are not modular like tank farms and require heavy machinery on site during the work-intensive construction phase on top of costs from site-specific planning and geological evaluations. A linear approximation of a CO_2 storage cavern investment cost would therefore be of the form (2):

Investment cost [M€] = a + b * storage volume [m^3] (2)

Determining such equations as 2 would require a good sampling of cavern investments that represent well the entire range of considered capacities. The available references, presented in Figure 18, from scientific literature are inadequate in numbers for such line fitting.

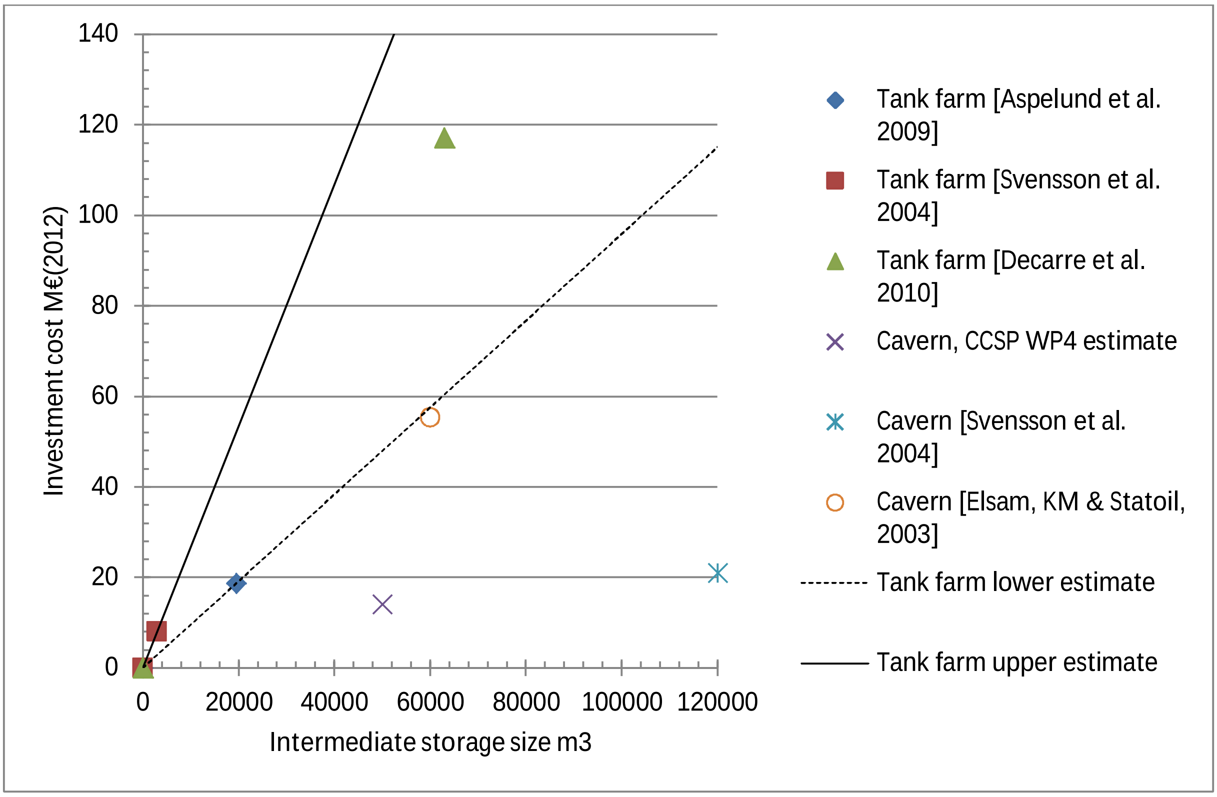


Figure 18: Comparison between investment cost of storage caverns and steel tanks, as found in literature. Refer to the references in Table 3.

As anticipated, the cavern investment costs seem lower than tank farm investments of the same volume. The cost references from Aspelund *et al*. (2009) and Svensson *et al*.

(2004) are for capacities of 60 000 m^3 and 120 000 m^3. The investment cost estimate done in the CCSP WP4 is for a cavern of 50 000 m^3.

In order to arrive at the desired linear cost equations for cavern storages, the investment cost around the included reference points will have to be extrapolated. In lack of reported references on how such measures are taken on refrigerated rock caverns, some freedom in choosing an applicable methodology is used here. In chemical and process industry, the benefit of scale in investment can often be adequately well approximated by using the following equation 3 (Suokko, 2010):

Investment at capacity c = (reference capacity / c) * reference investment^0,7 (3)

Equation (3) was used to calculate an even amount and distribution of extrapolates in the range of 50 000 to 120 000 m^3 for all three cavern investment cost references. The extrapolated points of the investment costs reported by Elsam, KM and Statoil were fitted with a linear equation (see equation 2) that represents the upper estimate of cavern storage investment. Similarly, a linear equation for lower estimate of cavern storage investment costs were fitted to the extrapolated points of the reference cost reported by Svensson *et al*. (2004). Finally, one linear cost equation was fitted on all extrapolates from the three reference points, resulting in an average estimate for cavern investment. The resulted estimates are given in Figure 19 and Table 4.

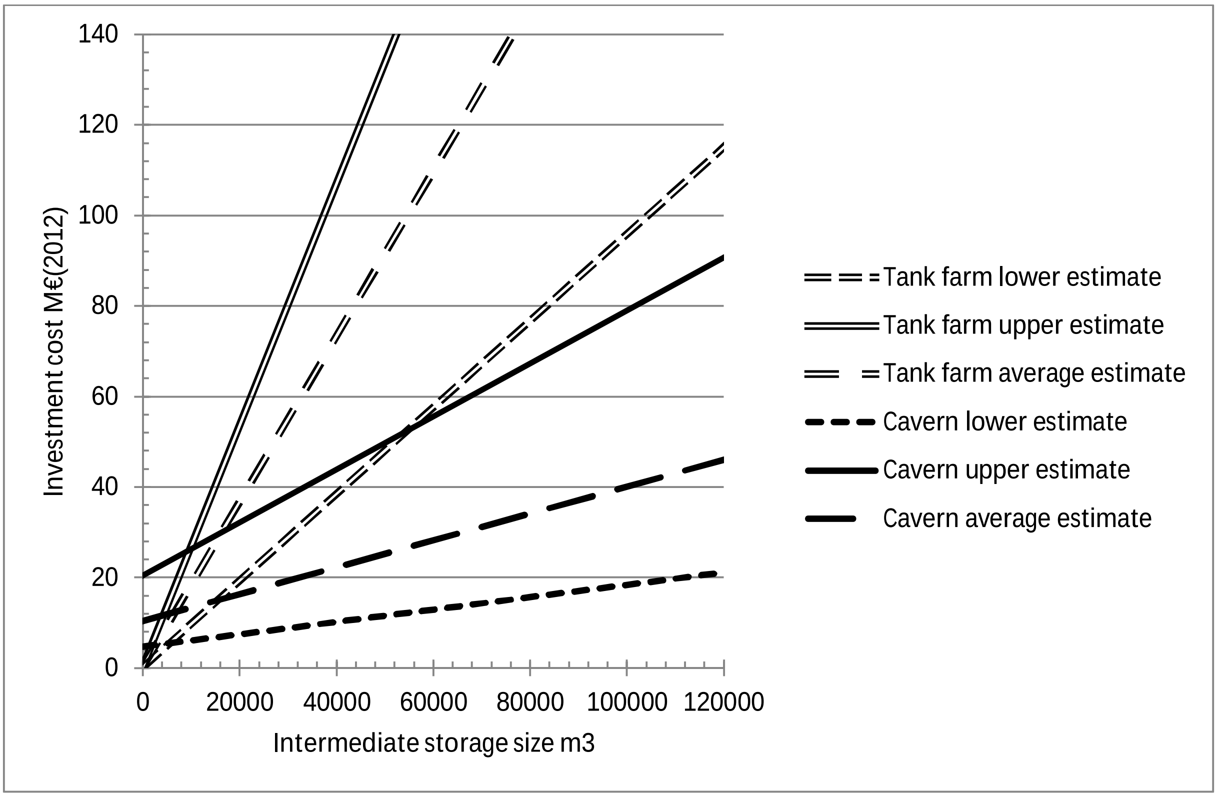


Figure 19: Upper, lower and average investment cost estimates for cavern and tank farm intermediate storages of CO2. Based on reference costs from Svensson et al. (2004), Aspelund et al. (2009), Decarre et al. (2010), Elsam, KM, Statoil (2003) and CCSP WP4 estimates.

Table 4: Linear investment cost equations of CO_2 intermediate storages fitted to the reference points from Svensson et al. (2004), Aspelund et al. (2009), Decarre et al. (2010), Elsam, KM, Statoil (2003) and CCSP WP4 estimates.

Estimates	Investment cost [M€] = a + b * storage volume [m^3]	
	a	b
Tank farm upper	0	0,0026698581
Tank farm average	0	0,0018292735
Tank farm lower	0	0,0009589744
Cavern upper	20,3896382947	0,0005857313
Cavern average	10,3337045343	0,0002968554
Cavern lower	4,7511020932	0,0001364845

According to Elsam, KM and Statoil (2003), a general conception within the industry is that cavern storages become economical compared to above-ground tanks approximately at capacities of over 50 000 m^3. The average linear estimates for cavern and tank farm storages in Figure 20 would suggest this break-even capacity would be significantly lower at below 10 000 m^3. Only the lower estimate for tank farm storages and the higher estimate for cavern storages seem to intersect roughly in the 50 000 m^3 region. Therefore, it is reasonable to assume that the average estimates presented in Figure 19 and **Error! Reference source not found.** might be overly high for tank farms and low for cavern storages. Adjusting the average linear estimates for cavern and tank farm storages evenly so they intersect at 50 000 m^3 would result in graphs presented in Figure 20.

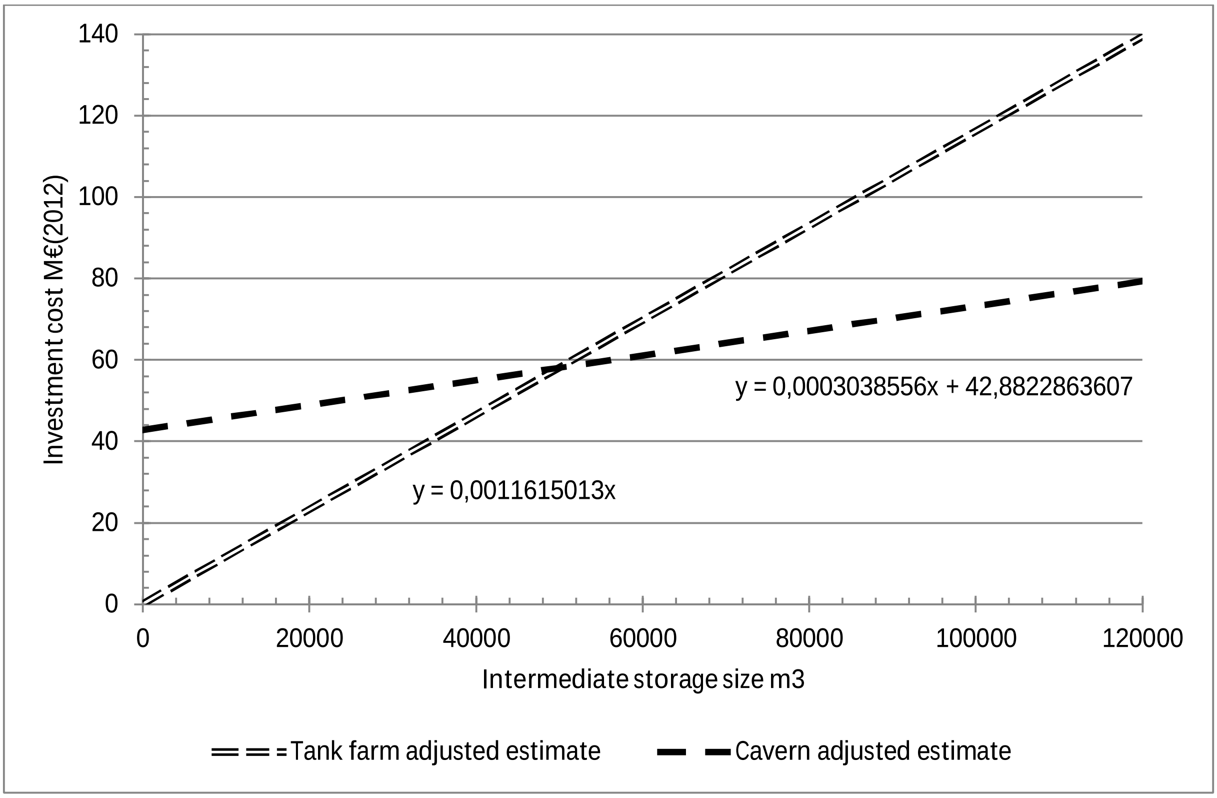


Figure 20: Adjusted linear average investment cost estimations for cavern and tank farm intermediate storages for CO_2. The adjusted investment cost for cavern storages only applies to capacity range of 50 000 – 120 000 m^3.

Compared to the estimates in Figure 19, the adjusted estimates fall, for the most part, between the lower and upper estimates for both cavern and tank farm storages. Here, only capacities between 50 000 and 120 000 m^3 are considered for cavern storages. As clarified in Figure 21, the reference cost for cavern storages all are below the adjusted linear investment cost estimate. Table 5 lists the differences of both the average and adjusted investment cost estimates from the lower and upper estimates presented in Table 4. Finally, the adjusted investment cost graphs are accompanied by the original investment cost references in Figure 21.

Table 5. Comparison of adjusted investment cost estimates to original cost estimates.

	Times lower estimate	Times upper estimate
Tank farm average	1,91	0,69
Tank farm adjusted	1,21	0,44
Cavern average[1]	2,18	0,51
Cavern adjusted[1]	4,20	0,98

[1]: The difference is taken at the middle of the capacity range for cavern storages, at 85 000 m^3.

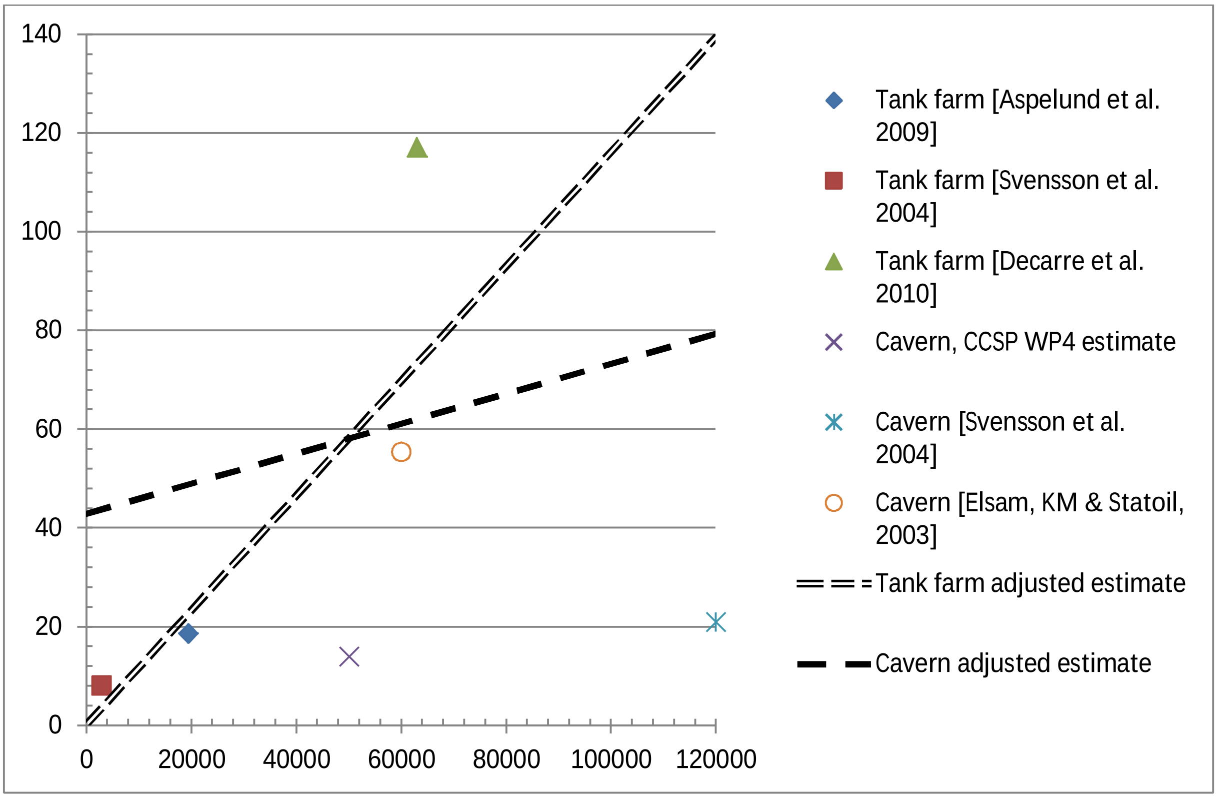


Figure 21: Adjusted linear intermediate CO_2 storage investment cost estimates compared to original cost references.

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 m^3 steel tank equals from 0,204 M€/a to 0,568 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 0,0288 M€/a to 0,0801 M€/a. The operation and maintenance costs represent therefore roughly 12% of the annual fixed costs of an above-ground CO_2 intermediate storage when costs related to liquefaction process are neglected. References for O&M costs of cavern storages suitable for CO_2 are not found in literature.

When the reliquefaction cost resulting from the operation of a single 3 000 m^3 tank unit is taken into account and the operation and maintenance costs are neglected, the annual cost of the unit amounts from 0,211 M€/a to 0,575 M€/a. This is based on IEA (2004) estimate that 0,2% of the stored cargo has to be evaporated per day out of storage tanks to compensate for the pressure build-up. The reliquefaction costs, equalling 0,00716 M€/a per a 3 000 m^3 tank, represent roughly 1-3% of the annual costs. On a rock cavern of a size of 50 000 m^3, the annual reliquefaction cost 0,023 M€/a equals some 2 % of the annual costs without operation and maintenance costs. The estimate is based on CCSP WP4 studies and assumes an electricity price of 40 €/MWh.

9 Conclusions

The results underpin the commonly assumed economic benefits from investing into caverns instead of modular on-ground tanks for larger intermediate storages for CO_2. In the light of the results, the rock caverns can become more economical compared to tank farm storages at capacities considerably under the 50 000 m^3 range reported by Elsam, KM, and Statoil (2004). 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 CO_2 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.

The investment costs were assumed in this study to scale linearly, as an adequate amount of data is not available to make reasonable curve fitting. The investment cost references in literature were also too few to determine the scalability of investment cost for cavern storages of various sizes. As a final remark, the results should not be extended to cover cavern storages of lower or higher volumes than in the range of 50 000 – 120 000 m^3.

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