Capture and Utilisation of CO_2

CO_2 Capture, Storage and Utilisation in Finland

CO_2:n erotus, varastointi ja hyötykäyttö Suomessa

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Abstract

The objective of the projects 'CO_2 capture technologies and their potential' and 'Carbon dioxide storage and reuse' was to 1) review the state of the art of the technologies, 2) evaluate the long-term storage options of CO_2 for Finland and possibilities to reuse captured CO_2, 3) evaluate the potential and cost to reduce Finland's CO_2 greenhouse gas emissions by CO_2 capture, storage and utilisation, and 4) identify opportunities for Finnish technology.

Several CO_2 separation and capture technologies exist today to produce CO_2 for commercial markets. The capture technologies may be applied before of after combustion of fossil fuel depending on the capture concept. The main options considered for the long-term storage of CO_2 are underground geologic formations. These include old oil and gas fields, coal formations and saline water aquifers. Deep oceans represent large potential sink for CO_2, but environmental uncertainties make it less feasible in the short term. Several demonstration projects are underway to evaluate technical, economical and environmental aspects of CO_2 sequestration. The estimated total cost with current technology for CO_2 sequestration ranges from 40–60 US$ per tonne CO_2 avoided. Most of the industrial applications do not offer long-term sink of CO_2, and currently the need is very small compared to the amount of emitted CO_2.

CO_2 capture and storage is more economical when applied on a large scale. The largest CO_2 emitting plants in Finland are oil refineries, coal-fired power plants and steel works. By applying CO_2 capture and storage technologies 80–90 per cent reduction of CO_2 emissions can be achieved. The costs were estimated only for the electricity sector. The CO_2 capture, transportation of CO_2 (1 000 km, onshore) and offshore storage would double the cost of electricity for natural gas and triple the cost for coal fired power plants compared to the current market price of electricity in Finland. According to this study, capturing CO_2 near the storage sites and investing in new cross-border electricity transmission capacity is a more feasible option. Storing CO_2 as solid mineral carbonate in Finland and integration of CO_2 capture concepts with industrial processes could be an option in the future.

Tiivistelmä

Projekteissa 'CO$_2$ erotusteknologioiden kartoitus ja potentiaali' ja 'Hiilidioksidin loppusijoitus ja hyötykäyttö' kartoitettiin CO_2-erotusteknologioiden ja -loppusijoituksen sekä -hyötykäytön nykytila. Tiedon avulla oli tavoitteena arvioida Suomen kasvihuonekaasupäästöjen vähentämisen potentiaalia ja kustannuksia sekä tunnistaa mahdollisuuksia suomalaiselle teknologialle.

On olemassa useita kaupallisia CO_2-erotusteknologiota, joita voidaan soveltaa ennen polttoprosessia tai sen jälkeen. Geologisia muodostumia, kuten ehtyneitä öljy- ja kaasulähteitä, hiiliesiintymiä ja suolavesikerrostumia, pidetään pääasiallisena pitkän aikavälin CO_2-loppusijoitusvaihtoehtoina. Valtameret ovat merkittävä mahdollinen loppusijoitusvaihtoehto, mutta ekologiset epävarmuustekijät estävät CO_2-varastoinnin valtameriin lähitulevaisuudessa. Käynnissä on useita demonstraatioprojekteja, joissa arvioidaan CO_2-varastoinnin teknis-taloudellista toteutettavuutta sekä ympäristö- ja turvallisuusnäkökohtia. CO_2-erotuksen ja -varastoinnin kokonaiskustannusten arvioidaan teknologioiden nykytasolla olevan 40–60 US$/ CO_2 (vältetty). CO_2:n hyötykäyttö teollisuudessa ei useinkaan muodosta pitkäaikaista CO_2-varastoa. Lisäksi tarve CO_2:lle teollisuuden raaka-aineena on erittäin vähäinen verrattuna CO_2 päästöihin.

CO_2-erotus ja -varastointi on kustannustehokkainta suuren mittakaavan sovelluksissa. Suomen suurimmat pistemäiset päästölähteet ovat öljynjalostamot, hiilivoimalaitokset sekä terästehtaat. CO_2-erotus- ja varastointiteknologioita käyttämällä on mahdollista vähentää CO_2 päästöjä 80–90 %. Kustannukset arvioitiin vain menetelmien soveltamiselle uusissa fossiilista polttoainetta käyttävissä lauhdevoimalaitoksissa. CO_2-erotus, -kuljetus (1 000 km, mantereella) ja -varastointi nostivat sähkön tuotantokustannukset kaksin-kolminkertaiseksi (maakaasu-kivihiili) verrattuna sähkön nykyiseen markkinahintaan. CO_2-erotus lähellä varastointipaikkaa ja investointi sähkönsiirtokapasiteettiin on tulosten perusteella kustannustehokkaampi vaihtoehto. Tulevaisuuden vaihtoehto Suomelle saattaisi olla myös CO_2-varastointi mineraalikarbonaattina ja CO_2-erotuksen ja -varastoinnin integrointi teollisuuden prosesseihin.

1 Introduction

Worldwide emissions from fossil fuel combustion are about 25 Gt of CO_2 per year. Approximately one third of all CO_2 emissions due to human activity come from fossil fuels generating electricity. Several industrial processes also emit large amounts of CO_2, like oil refineries, cement works, and iron and steel production. The Intergovernmental Panel on Climate Change (IPCC) has indicated that emission reductions of 50–60% are required to avoid dangerous interference with the climate. To make such deep reductions in global emissions, for example, CO_2 emissions from power production should be reduced by 90% (IEA GHG 2001a). Fossil fuels may continue to be used if the CO_2 produced was captured and put into long-term storage. CO_2 capture and storage is already possible, and currently several demonstration projects are underway. Capturing and storing CO_2 would not need major changes to processes, and widespread use of this technique could be achieved without the need for rapid change in the energy supply infrastructure.

In 1999, Finland's CO_2 emissions from fossil fuel combustion were 56.8 million tonnes of CO_2-eq. The annual greenhouse gas (GHG) emissions, however, depend on hydropower production in the Nordic counties, the demand of heating energy and the degree of economic growth. On the average, in the 1990's the total GHG emissions have grown slightly, but the annual variation has been quite large due to variations in hydropower production and imported electricity. The total GHG emission of all Kyoto gases were roughly about the same level as in 1990 due to decreases of emission in other sectors like waste management and agriculture. The net growth of the forest biomass caused a biological sequestration impact varying annually between 10 and 35 million tonnes in the 1990's (Pipatti et al. 2001). Only a small fraction of this biological net sink can be accounted in the fulfilment of Kyoto Protocol commitments according to the agreements made at the Bonn and Marrakech negotiations between the parties of Climate Convention.

The objective of the projects 'CO$_2$ capture technologies and their potential' and 'Carbon dioxide storage and reuse' was to 1) review the state of the art of the CO_2 capture technologies, 2) evaluate the long-term storage options of CO_2 for Finland and possibilities to reuse captured CO_2, 3) evaluate the potential and cost to reduce Finland's CO_2 greenhouse gas emissions by CO_2 capture, storage and utilisation, and 4) identify opportunities for Finnish technology.

The costs were evaluated only for the electricity sector and new condensing fossil fuel fired power plants. Due to limited possibilities to store CO_2 in Finland, a part of the research was focused on the application of technologies in Finland and part of the work was concerned with application of CO_2 capture and storage technologies near the storage sites and importing the energy in the form of electricity or hydrogen to Finland.

2 Description of technologies

2.1 CO_2 capture technologies and concepts

A wide range of CO_2 separation and capture technologies exists today to produce CO_2 for commercial markets. The capture technologies may be applied before or after combustion depending on the capture concept. Concepts for capturing CO_2 can be divided into three main categories:

1. Post-combustion decarbonisation (Flue Gas Scrubbing)
2. Pre-combustion decarbonisation
3. Novel combustion concepts (Oxygen Combustion).

The main CO_2 capture technologies are absorption, adsorption, cryogenics and membranes.

Capture of CO_2 is best carried out at large point sources, such as power stations, oil refineries, petrochemical, fertiliser and gas processing plants, steel works and pulp and paper mills (U.S. DOE 2001).

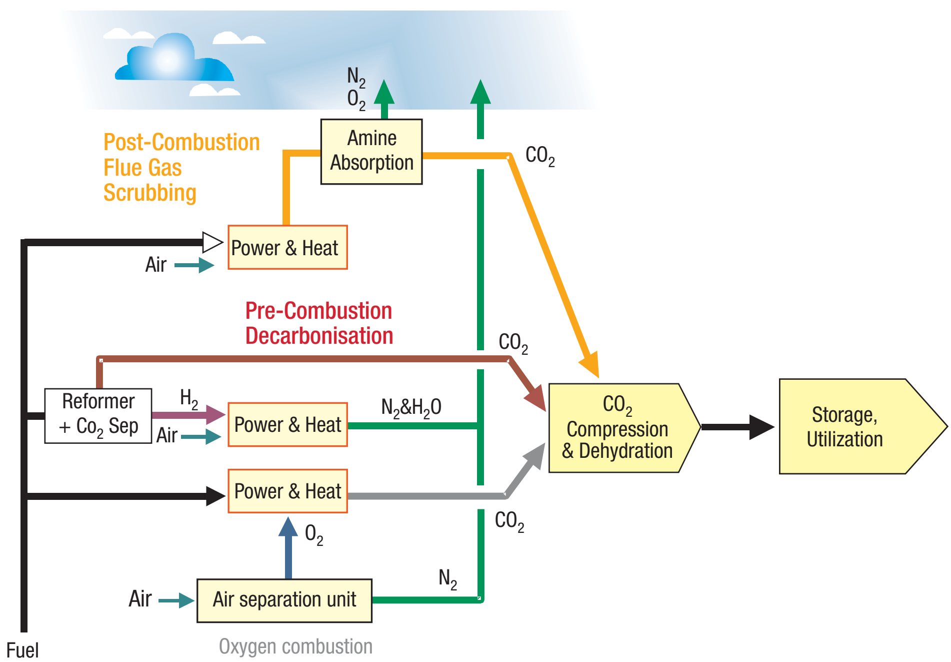

Figure 1. CO_2 capture concepts in energy production (Joint Industry Carbon Capture Project 2002).

2.2 CO_2 storage

The captured CO_2 should be concentrated and pressurised into a liquid or gas stream suitable for transportation and sequestration. Major options considered for the final storage of CO_2 are deep underground geological formations, such as depleted oil and gas fields, deep coal seams, salt domes, rock caverns, and deep aqueous formations including saline formations. The geologic formations are widespread and have large potential for CO_2 sequestration. Also, deep oceans represent a large potential sink for anthropogenic CO_2 storage. Table 1 shows the estimates of global capacity of CO_2 storage reservoirs.

CO_2 storage in hydrocarbon reservoirs should have economical advantages over storage in aquifers or ocean. Enhanced oil (EOR) recovery has the commercial benefit of sequestering CO_2 while increasing production from active oil fields. Deep, unmineable coal beds provide an opportunity to simultaneously sequester CO_2 and increase the production of natural gas (IEA GHG 2001b).

Advanced chemical approaches to CO_2 sequestration could allow gaseous CO_2 to be transferred into inert and long-lived solid materials. A suggestion of a process that would bind anthropogenic CO_2 is to convert naturally occurring mineral oxides to carbonates. For mineral carbonation the use of

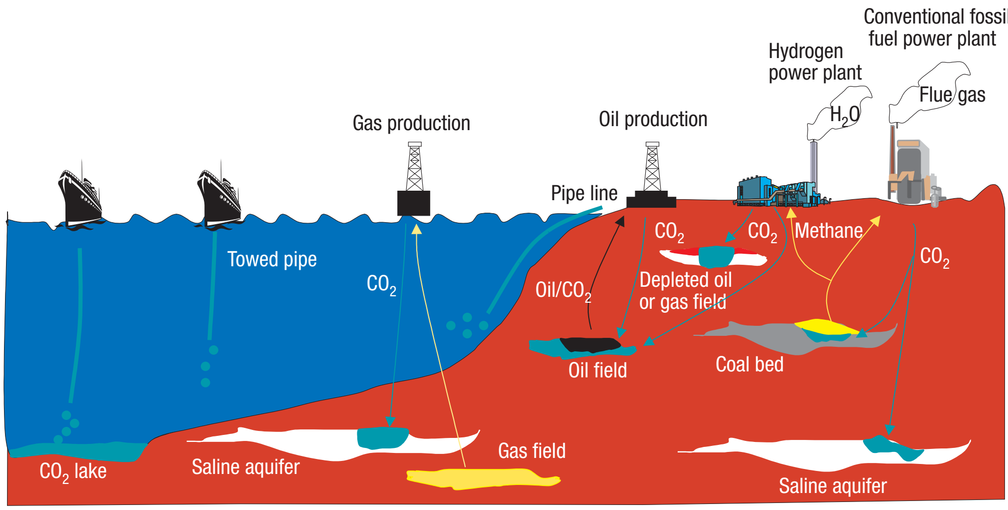

Figure 2. Illustration of major options considered for the final storage of CO_2.

Table 1. Estimates of global capacity of CO_2 storage reservoirs compared with projected total emissions between 2000 and 2050, according to 'business as usual scenario' (IEA GHG 2001b, Edmonds et al. 2000, IEA GHG 2000a).

Carbon storage reservoir	Range, Gt CO_2	% of emissions to 2050
Deep ocean	5 000–100 000	250–5 000
Deep saline reservoirs	400–10 000	20–500
Depleted gas reservoirs	800	40
Depleted oil reservoirs	120	5
Unmineable coal seams	> 15	> 1

magnesium based silicates, $xMgO \cdot ySiO_2 \cdot zH_2O$ is favoured, because they are worldwide available in huge amounts. These natural resources may be capable of binding all fossil fuel-bound carbon (Ziock 2002, Lackner and Ziock 2000). Magnesium silicates can be divided into several subgroups. The largest quantities are olivine, $(Mg,Fe)SiO_4$, and serpentine, $Mg_3Si_2O_5(OH)_4$. Large-scale flue gas CO_2 sequestration as mineral carbonates would, however, require enormous amounts of mineral, and it may be very energy consuming. Another option is the formation of CO_2 hydrates, an ice-like material ($CO_2 \cdot nH_2O$), which may be sequestered on the ocean floor (IEA GHG 2000b).

2.3 Direct utilisation of CO_2

Wide range physical and chemical properties of CO_2 make it a key part in countless industrial and chemical applications, either in gaseous, liquid or solid forms. The current industrial need is very small compared to the amount of emitted CO_2. For example, in the USA, the industrial need of CO_2 is only about 2% of the emitted CO_2, and about 80% of this amount is used in EOR. In countries, which do not have oil production, the industrial usage of CO_2 is usually considerably lower. Another problem is that most of the applications do not offer long term sink of CO_2.

In utilisation of captured CO_2, net reduction of CO_2 emissions takes place only if captured CO_2 replaces CO_2 that is at present produced from fossil fuel. The most examined alternatives of direct utilisation fall into three categories: industrial uses, chemical conversion to fuels, and biological conversion to fuels. Although direct utilisation of CO_2 would not solve the problem of global warming, the potential income that it might generate would reduce the burden of disposal (RUCADI 2001, Crabb 2000).

3 Development of technologies

The major barriers for applying CO_2 separation and capture technologies and concepts are, in addition to issues related to storage or utilisation of CO_2, the high capital and operating costs and reduced efficiencies. The cost of avoided emissions for the capture stage (including pressurisation for transport) is 30–50 US$/t CO_2 and the total cost (including also CO_2 storage and transport) 40–60 US$/t CO_2 (IEA GHG 2001b). However, opportunities exist for significant reductions in costs and energy requirement, and there appear to be niches wherein CO_2 sequestration may be competitive among other long-term mitigation technologies, like large-scale renewable energy production.

Post-combustion technologies like monoethanolamine (MEA) absorption can be considered commercial, although there is still room for improvement. There are several R&D Programmes going on that look for possibilities to reduce the costs significantly in the future. The goal of Joint Industry Carbon Capture Project cofunded by several large oil companies, U.S. DOE, EU and Norway, for example, is to reduce the costs for CO_2 capture and storage in geological formations by 50 % when applied to retrofit and 75 % when applied to new build applications compared with current best available technology. There are also several demonstration projects underway to evaluate technical, economical and environmental feasibility of CO_2 storage in geological formations.

Significant cost reductions require radical changes to combustion technologies, and it is estimated that it will take 5 to 10 years before these concepts are translated into commercial processes (Joint Industry Carbon Capture Project 2002, U.S. DOE and NETL 2002)

- CO_2 capture and storage technologies and concepts are mainly being developed in the following programmes and countries:
- Joint Industry Carbon Capture Project (http://www.co2captureproject.com)

- IEA GHG R&D Programme (http://www.ieagreen.org.uk)
- EU funded projects
- US Carbon Sequestration Programme (http://fossil.energy.gov/coal_power/sequestration)
- Japan (NEDO, http://www.nedo.go.jp/GET/e11.html)
- Norway (Klimatek, http://program.forskningsradet.no/klimatek)

4 Potential and cost of CO_2 capture and storage for Finland

4.1 Industrial CO_2 capture and utilisation in Finland

In Finland the largest CO_2 consuming industries are pulp and paper, beverage, food processing and metal industries. Currently, industrial needs for CO_2 are mostly covered by captured CO_2 in Finland. Three CO_2 capture plants exist in connection with hydrogen, alcohol and calcium chloride production. The total capacity of these capture plants is about 70 000 tonnes of CO_2 per year. Finland's beverage industry also has additional CO_2 capture plants, which reduces the amount of purchased CO_2 for beverage production. CO_2 is also produced for greenhouses by burning fossil fuels.

Recently, especially in the Finnish pulp and paper industries, innovative CO_2 gas applications have been developed, and they are presently in use at a number of large mills. The CO_2 applications have been introduced especially for recycled paper. In food processing industries, CO_2 usage has also grown to increase food safety. In the 1990's, Finland's beverage sales increased from 230 million to 360 million litres. It is assumed that beverage production in Finland may still increase to some degree, but not to the same extent as in the 1990's. The potential to reuse captured CO_2 in industry is less than 0,5% of Finland's anthropogenic emissions. On the other hand, various industrial processes like pulp and paper manufacturing processes could offer niches, wherein CO_2 capture processes could become economical. The possible growing industrial need of CO_2 in Finland may not be covered by existing CO_2 production plants, which indicates that there might be niches for new processes to capture and produce CO_2 (Koljonen et al. 2002).

4.2 Large scale CO_2 capture and storage from Finland's perspective

As CO_2 capturing would be more economical on a large scale, the largest CO_2 emitting point sources were evaluated. The largest CO_2 emitting plants in Finland are oil refineries, coal-fired power plants and steel works. Five to ten plants produce more than 1 million tonnes of CO_2 annually. In pulp and paper industry, an increased amount of biofuels used in heat and power generation has decreased CO_2 emissions considerably. The CO_2 emissions of coal-fired condensing power plants vary a lot from year to year. If the annual amount of rainfall is high in the Nordic countries, hydropower production is high and more electricity is imported to Finland. During dry seasons Finland exports electricity, which is mainly produced by condensing coal fired power plants. To meet the targets for greenhouse gas emission reduction in the long term, the CO_2 sequestration might be one option among many emission reduction alternatives. By applying CO_2 capture and storage technologies 80–90 per cent reduction of CO_2 emissions can be achieved.

In Finland, no suitable geologic formations exist to sequestrate CO_2. Further, the oceans nearby Finland are not deep enough for considering CO_2 storage in oceans. The nearest potential CO_2 sequestration sites are offshore oil and gas fields and saline aquifers in the North Sea and Barents Sea. This would mean a 500 to 1 000 km CO_2 transmission depending on the location of the CO_2 capture plant (Koljonen et al. 2002).

Storing CO_2 as mineral carbonate could be an option for Finland, since large resources of suitable silicates exist in Finland as natural minerals and as wastes of mining industry. Most of the mineral deposits are found in Central and Northern Finland.

However, mineral carbonation may be very energy consuming and thus in a recent study (Kohlmann et al. 2002) reaction pathways with minimum energy input were addressed. It was concluded that the mineral carbonation process has to involve the release or activation of the mineral's MgO content before the reaction with CO_2 to $MgCO_3$, which could imply a two-stage process. Water catalyses the carbonation reaction somewhat, which makes the use of serpentine (its 10–14%-wt crystal water is released) more attractive than other MgO-containing minerals (olivine, fosterite). CO_2 will have to be transported to a suitable mineral deposit since transporting minerals to/from CO_2 emission sources will present unacceptable costs. Fortunately, process integration with mining activities may be very advantageous from cost and energy consumption points of view, possibly allowing for, e.g., higher valuable metal extraction rates as well. Further research will concentrate on reaction kinetics and large-scale integrated processing based on direct, dry carbonation of MgO-containing mineral with pressurised CO_2 from a separate capture process (Kohlmann et al. 2002).

4.3 Costs of application of CO_2 capture and storage in electricity production in Finland

4.3.1 New fossil fuel fired power plant in Finland with CO_2 capture

The economic feasibility of CO_2 capture by conventional chemical absorption was evaluated for 660–790 MW_e conventional natural gas fired combined cycle (NGCC) and for 360–500 MW_e pulverized coal once through boiler (PF). The CO_2 capture process was integrated with a green field power plant. The estimated costs of 1 000 km pipeline transmission to storage site and offshore storage of CO_2 were included in the evaluation. The data was collected form literature for power plant concepts and for CO_2 capture process. For transmission and storage of CO_2 and energy, a spreadsheet-based model recently published by IEA Greenhouse Gas R&D Programme (IEA GHG 2002) was used as well. The results of the evaluations are presented in Figures 3 and 4. The electricity market price is the average electricity price in the Nordic Power Exchange, which is the world's

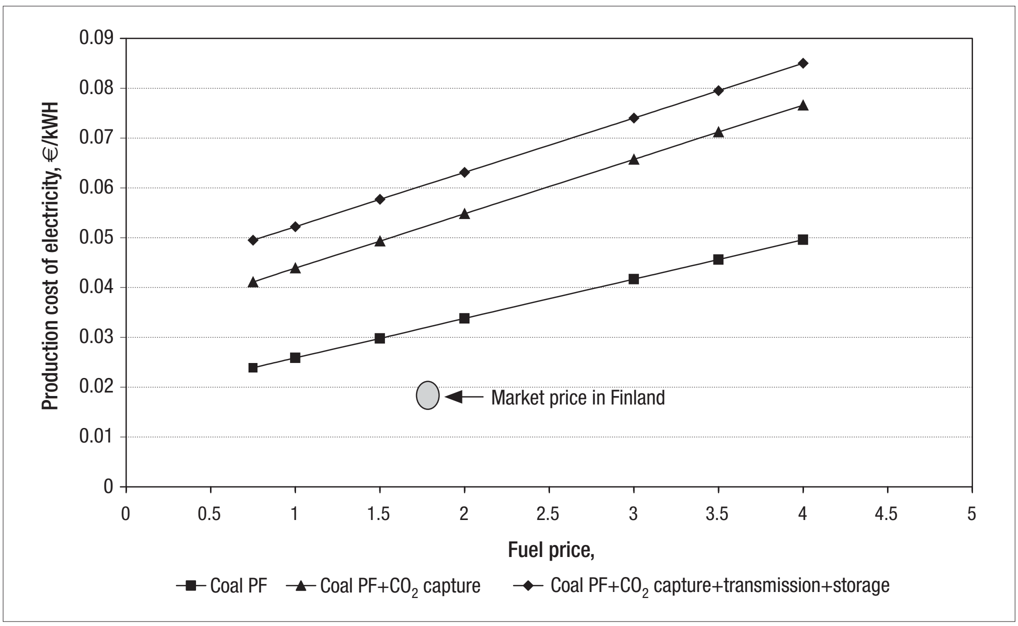

Figure 3. Power production costs for a condensing coal fired power plant with CO_2 capture (includes gas compression), 1 000 km onshore pipeline transmission of CO_2 and offshore CO_2 geological storage (discount rate 5%, plant life 25 years, operating time annually 8 000 h).

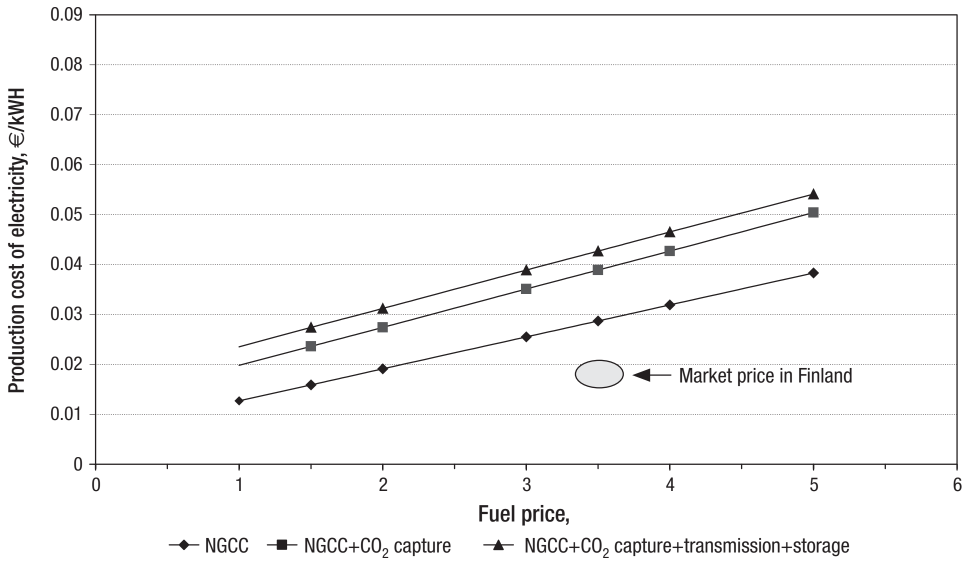

Figure 4. Power production costs for a condensing natural gas fired power plant with CO_2 capture (includes gas compression), 1 000 km onshore pipeline transmission of CO_2 and offshore CO_2 geological storage (discount rate 5%, plant life 25 years, operating time annually 8 000 h).

first international commodity exchange for electrical power.

As shown in the figures 3 and 4, the production cost of electricity for coal fired power plant would be about three times higher than the average electricity market price in Finland if the investment and operating costs of CO_2 capture, transmission and storage were included. For natural gas fired power plant, the corresponding electricity production cost would be about two times higher than the current market price of electricity (Koljonen et al. 2002).

4.3.2 Application of technologies closer to storage sites as an alternative

Application of technologies closer to the storage sites was compared with application of technologies in Finland. The options included in the study were:

1. Natural gas is imported by existing pipeline and electricity produced by NGCC in Finland. The captured CO_2 is transported by a 1 000 km onshore pipeline and sequestered offshore.
2. Carbon-free fuel, i.e. hydrogen, is imported into Finland by a 1 000 km onshore pipeline. In this scenario, fuel is decarbonized near the storage site and CO_2 is sequestered offshore.
3. Electricity is produced near the sequestration place and imported into Finland. CO_2 is sequestered offshore. Cross-border DC electricity transmission capacity is increased by a given amount.

In figure 5, investment costs of the above scenarios are shown. In the calculations, fuel efficiency has been increased to cover the losses of electricity transmission, initial gas compression and/or gas transmission. Preliminary results indicated that CO_2 transport and electricity transmission would be the most feasible options with such long transmission distances. Considering environmental and safety issues, electricity transmission would become the most feasible option. However, it should be noted, that the investment costs of hydrogen alternative have remarkable uncertainty, and a more detailed analysis should be performed before final conclusions (Koljonen et al. 2002).

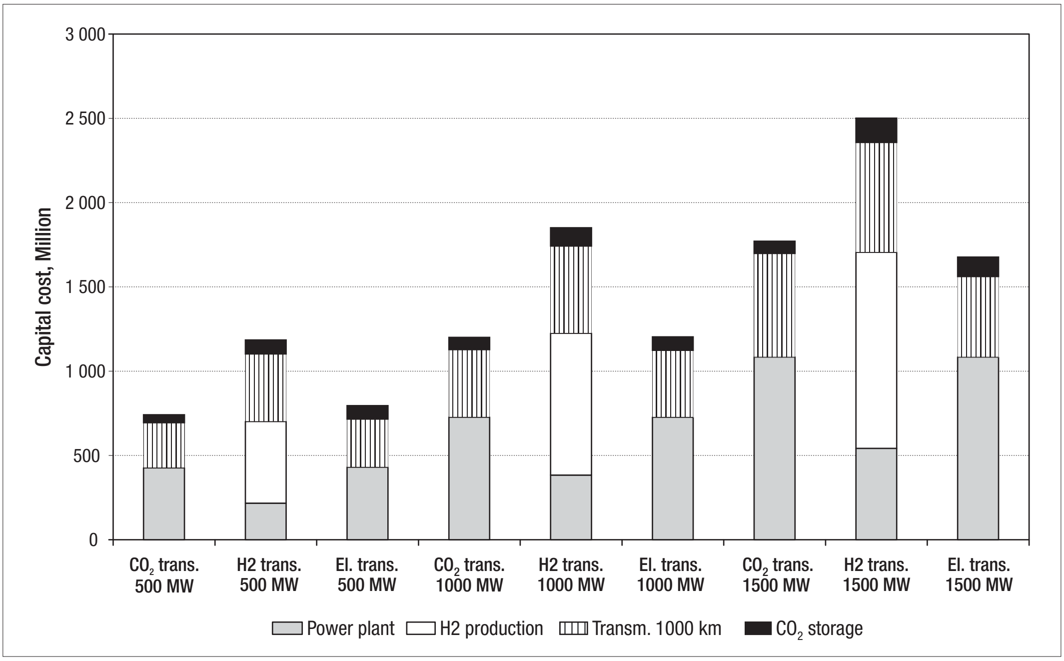

Figure 5. Comparison of investment costs of three CO_2 management scenarios for Finland.

4.4 Opportunities for Finnish technology

Because of the relatively short history of the development of CO_2 capture technologies and concepts, there is still room for new ideas and need to improve the existing concepts. Opportunities exist e.g. in developing Finnish power plant technologies into a zero or low-CO_2 emitting direction. Also, development of CO_2 capture technologies and concepts that can be integrated to various industrial process, especially processes that employ Finnish technology, could offer niches, wherein CO_2 capture would become economical.

Storing CO_2 as mineral carbonate could be an option, since large resources of suitable silicates exist in Finland as natural minerals and as wastes of mining industry. The most important positive feature, which justifies further work on improvement of this technology, is that CO_2 as $MgCO_3$ is a stable compound and environmentally acceptable solution for a long term storage of CO_2. It is also the only currently known alternative for Finland to store CO_2 (Kohlmann et al. 2002, Koljonen et al. 2002).

5 Discussion and conclusions

The lack of long-term CO_2 storage sites in Finland, together with long transmission distances to the closest storage sites abroad would be the greatest barriers to overcome before the implementation of the CO_2 capture and long-term storage technologies in emission management. The production cost of electricity would be approximately doubled for NGCC with CO_2 capture, onshore transmission and offshore storage. For coal fired power plant, the corresponding electricity production cost would be even higher. According to this study, capturing CO_2 near the storage sites and investing in new cross-border electricity transmission capacity seems to be a more feasible option. Mineral carbonation could be a future option for Finland, but the reaction kinetics of carbonation process still has to be investigated before any final conclusions could be made.

The potential to reuse captured CO_2 in industry is less than 0.5% of Finland's anthropogenic emissions. On the other hand, various industrial processes like pulp and paper manufacturing processes, could offer niches, wherein CO_2 capture process could become economical. However, quite few CO_2 reuse options in Finland offer long-term carbon sinks.

There is still room for new ideas and for improvement of existing CO_2 capture technologies and concepts, especially pre-combustion and novel combustion concepts. Opportunities exist e.g. in developing Finnish power plant technologies into zero or low-CO_2 emitting direction. Integration of CO_2 capture technologies and concepts in industrial processes is less studied a subject compared with energy production. Developing CO_2 capture technologies and concepts that can be integrated to various industrial processes, especially processes that employ Finnish technology, could offer new possibilities in the future.

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