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CCSP Carbon Capture and Storage Program

Mid-term report 2011–2013

VTT

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CCSP Carbon Capture and Storage Program. Väliraportti 2011–2013.
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Abstract

Carbon Capture and Storage (CCS) is considered to be one of the main options for reducing global CO_2 emissions. However, the development of CCS technology faces many challenges. CO_2 capture is still very energy intensive and development is needed to bring costs down. Also, CO_2 needs to be transported to a suitable storage site for secure and permanent storage. Although CCS technology has not yet been implemented at a full-scale power plant, several demonstration projects are underway in the world.

The report gives an overview of the work carried out in the Carbon Capture and Storage Program (CCSP) R&D program during 2011–2013. The R&D program is coordinated by CLEEN Ltd. with funding from Tekes – the Finnish Funding Agency for Technology and Innovation. The objective for CCSP is to develop CCS-related technologies and concepts, leading to essential pilots and demonstrations by the end of the program. A further objective is to create a strong scientific basis for the development of CCS technology, concepts and frameworks, and to establish active, international CCS co-operation. The program consortium consists of 9 research organisations and 17 industrial partners, with an annual budget of about 3 million euro per year.

For Finland, CCS offers significant opportunities, which are being investigated and developed in CCSP. Being a large consumer of power and heat, Finland has a unique opportunity in integrating CCS with combined heat and power (CHP) plants. As Finland is a large consumer of biomass, adding CCS to bioenergy solutions (bio-CCS) would enable removal of CO_2 from the atmosphere. For heavy industry, such as oil refining and steel manufacturing, CCS is the only technology that can significantly reduce CO_2 emissions. For the Finnish technology developers and providers CCS could provide a significant market share in the future, such as in the area of oxy-fuel combustion and chemical looping combustion, which are being further developed in CCSP. Monitoring technologies is another quickly developing area where a growing Finnish expertise can help making CCS a safe and secure emission reduction and improve the social acceptance of CCS. As the Finnish bedrock does not have any formations suitable for underground storage of CO_2, other options are being investigated. A recent survey of the Baltic Sea area shows a potential for geological storage of CO_2. Several options for using CO_2 as a raw material for production of inorganic carbonates, chemicals and fuel components also show promise.

Keywords CCS, CCSP, Cleen, CO_2, capture, storage, sequestration

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Tiivistelmä

Hiilidioksidin talteenotto ja varastointi on keskeisimpiä keinoja hillitä maailmanlaajuisia hiilidioksidipäästöjä. Kyseiseen teknologiaan liittyy kuitenkin vielä lukuisia kustannuksia lisääviä haasteita, joista keskeisenä on talteenottoprosessin korkea energiaintensiivisyys. Hiilidioksidi on myös kuljetettava pysyvään ja turvalliseen geologiseen varastointiin soveltuvaan sijaintiin. Hiilidioksidin talteenottoa ei ole sovellettu vielä täyden mittakaavan laitoksilla, mutta useita demonstraatioluokan projekteja on joko vireillä tai käynnissä maailmalla.

Tämä raportti antaa yleissilmäyksen työhön, joka on tehty Carbon Capture and Storage Program (CCSP) -tutkimusohjelmassa vuosina 2011–2013. Ohjelmaa koordinoi CLEEN Oy. Teknologian ja innovaatioiden kehittämiskeskus Tekes on mukana rahoittamassa ohjelmaa. CCSP:n tarkoituksena on kehittää CCS:ään liittyviä teknologioita ja konsepteja, johtaen näistä keskeisimpien pilot-kokeisiin ja demonstraatioihin ohjelman loppuun mennessä. Tavoitteena on myös vahvistaa tieteellistä pohjaa CCS:n lainsäädännöllisen ja sosiaalisen viitekehyksen tutkimuksessa. Lisäksi ohjelman pyrkimyksenä on edesauttaa aktiivista ja dynaamista kansainvälistä yhteistyötä CCS:n saralla. Ohjelman konsortio koostuu yhdeksästä tutkimusorganisaatiosta ja 17 teollisuuspartnerista. Vuosibudjetti on n. 3 miljoonaa euroa.

Hiilidioksidin talteenotto ja varastointi tarjoaa Suomelle merkittäviä mahdollisuuksia, joita tutkitaan ja kehitetään CCSP:ssä. Sähkön ja lämmön suurkuluttajana Suomella on ainutlaatuinen mahdollisuus soveltaa CCS:ää yhdistetyn sähkön ja lämmöntuotannon laitoksiin (CHP). Soveltamalla CCS-teknologiaa puolestaan Suomen moniin biomassaa polttaviin laitoksiin hiilidioksidia voitaisiin käytännössä poistaa hiilikierrosta ja siten ilmakehästä. Raskaalle teollisuudelle, kuten öljyn jalostukselle ja teräksen tuotannolle, CCS on ainoa teknologia, joka mahdollistaa voimakkaan hiilidioksidipäästövähennyksen. Suomalaiselle teknologiateollisuudelle CCS avaa markkinoita ja liiketoimintamahdollisuuksia uusien teknologisten ratkaisujen myötä. Näistä esimerkkejä ovat kemiallisiin hapenkantajiin perustuva polttoteknologia sekä happipolttoteknologia, joita kehitetään CCSP-ohjelmassa. Monitorointiteknologia on myös nopeasti kehittyvä alue, jolla kasvava suomalainen osaaminen voi parantaa CCS:n luotettavuutta ja turvallisuutta sekä myös edesauttaa teknologian julkista hyväksyntää. Suomen maaperästä ei kuitenkaan löydy soveltuvia geologisia muodostumia, joten ohjelmassa keskitytään muihin vaihtoehtoihin. Viimeaikaisen tutkimustiedon valossa Itämeren alueella on potentiaalia hiilidioksidin geologiseen varastointiin. Useat vaihtoehdot hiilidioksidin käyttämiseksi epäorgaanisten karbonaattien, kemikaalien sekä polttoaineiden valmistamisessa näyttävät myös lupaavilta.

Avainsanat CCS, CCSP, Cleen, CO_2, talteenotto, varastointi, hiilidioksidi

Preface

The work presented in this report was carried out in the Carbon Capture and Storage Program (CCSP) research program coordinated by CLEEN Ltd. with funding from Tekes – the Finnish Funding Agency for Technology and Innovation, during 2011–2013. The CCSP consortium consists of 17 industrial partners and 9 research partners. Industrial partners are Forum Oyj, Ramboll Finland Oy, Vibrometric Oy, Helsingin Energia, Gasum Oy, Neste Oil Oyj, Foster Wheeler Energia Oy, Ruukki Metals Oy, Neste Jacobs Oy, Fortum Power and Heat Oy, Stora Enso Oyj, ÅF-Consult Oy, Oulun Energia, Tapojärvi Oy, Nordkalk Oy Ab, Andritz Oy, and Outotec Oyj. Research partners are VTT Technical Research Centre of Finland, Aalto University, Lappeenranta University of Technology, Geological Survey of Finland, Tampere University of Technology, University of Oulu, Åbo Akademi University, University of Tampere and the Finnish Environment Institute SYKE.

The report has been edited together from internal periodic and intermediate reports as well as work documents that were never published. Thanks therefore goes to the Program Committee of CCSP for putting together internal periodic and intermediate reports and reviewing the report: Antti Arasto, Eerik Järvinen, Jussi Laitio, Markku Raiko, Matti Nieminen, Erkki Pisilä, Reijo Kuivalainen Risto Sormunen, Sari Siitonen, Timo Hyppänen, Timo Laukkanen, Eemeli Tsupari and Sebastian Teir. In addition Tero Tynjälä, Calin Cosma, Jouko Ritola, Joonas Virtasalo, Nicklas Nordbäck, and Sari Luste are acknowledged for providing material for the reports, and everyone else working in CCSP.

Contents

List of symbols

2-HEAA	2-(hydroxy) ethylammonium acetate
ASU	Air separation unit
AMP	2-amino-2-methyl-1-propanol
Bio-CCS	Bioenergy with carbon dioxide capture
CCGT	Combined cycle gas turbine
CCS	Carbon capture and storage
CCSP	Carbon Capture and Storage Program
CCUS	Carbon capture, utilisation and storage
CFB	Circulating fluidized bed
CFD	Computational fluid dynamics
CGS	CO_2 Geological storage
GHG	Greenhouse gas
CHP	Combined heat and power
CLC	Chemical looping combustion
CPU	Compression and purification unit
DEA	Diethanolamine
DECHEMA	Society for Chemical Engineering and Biotechnology
DIPA	Diisopropanolamine
DMC	Dimethylcarbonate
DNPH	2, 4-Dinitrophenylhydrazine
DSC	Differential scanning calorimetry
EASAC	the European Academies Science Advisory Council
EC	the European Community
EEA	the European Environment Agency
EEA	European Economic Area
EERA CCS JP	European Energy Research Alliance, CO_2 Capture and Storage Joint Programme
EHS	Environment, health and safety

EPA	United States Environmental Protection Agency
E-PRTR	the European Pollutant Release and Transfer Register
EU ETS	EU's Emissions Trading System
FINAS	Finnish Accreditation Service
FINLEX	Online database of up-to-date legislative and other judicial information of Finland
GCCSI	Global Carbon Capture and Storage Institution
GHG	Greenhouse gas
HAc	Acetic acid
HRSG	Heat recovery steam generator
IEA GHG	the IEA Greenhouse Gas R&D Programme
IGU	International Gas Union
LCA	Life cycle analysis
LPG	Liquefied petroleum gas
LUT	Lappanranta University of Technology
MDEA	Methyldiethanolamine
MEA	Monoethanolamine
MEP	Member of European Parliament
MSP	Moving source profiling
NDELA	N-nitrosodiethanolamine
PBR	Photobioreactor
PCC	Precipitated calcium carbonate
SLE	Solid-liquid equilibrium
SMR	Steam methane reforming
Tekes	the Finnish Funding Agency for Technology and Innovation
VLE	Vapour-liquid equilibrium
VSP	Vertical seismic profiling
WGS	Water-gas shift
ZEP	the European Technology Platform for Zero Emission Fossil Fuel Power Plants
ÅA	Åbo Akademi

1. Introduction

Carbon Capture and Storage (CCS) is considered to be one of the main options for reducing CO_2 emissions alongside renewable energy, more efficient energy use and nuclear power. The concept of CCS includes capture of CO_2 produced by a power plant or an industrial plant, transportation of CO_2 to a suitable storage location, and permanent storage of CO_2 (underground or as inert carbonates) in isolation from the atmosphere (Figure 1). CCS could significantly reduce CO_2 emissions and contribute significantly in achieving the deep emission cuts needed to stabilize the global temperature rise. According to a recent study, Finland has good opportunities to achieve a GHG emission reduction of 80% by 2050 if all the technology options are available (Koljonen et al. 2012). CCS was especially found important for heavy industry, which has less mitigation options than the energy production industry has.

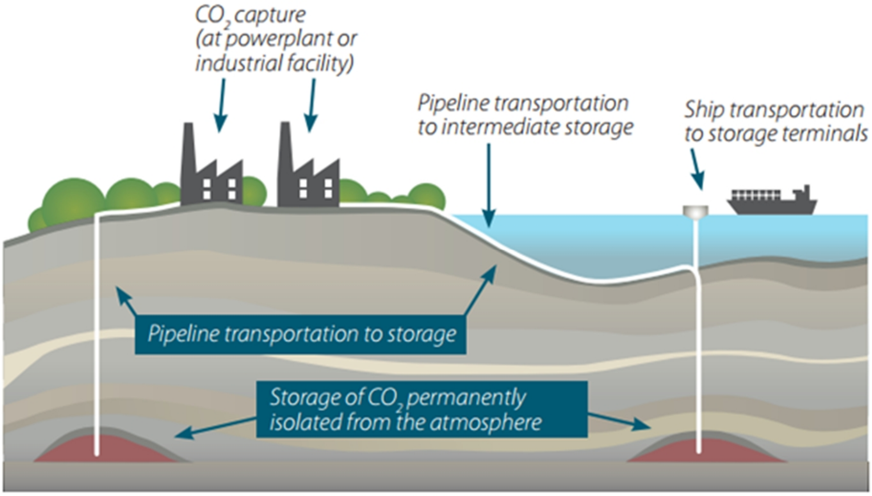


Figure 1. The basic principle for Carbon Capture and Storage (CCS).

1.1 CCS – Significant opportunities for Finland and Finnish stakeholders

The development of CCS technology faces many challenges. CO_2 capture processes are currently very energy intensive and development is needed to bring costs down. Also, CO_2 needs to be transported to a suitable storage site for secure and permanent storage. Although CCS technology has not yet been implemented at a full-scale power plant, several demonstration projects are underway in the world. According to GCCSI (2012), eight projects are in operation, storing 23 Mt CO_2 per year, mostly in conjunction with enhanced oil recovery (EOR).

CCS offers significant opportunities to implementation in Finland. Being a large consumer of power and heat, Finland has a unique opportunity in integrating CCS with combined heat and power (CHP) plants. As Finland is a large consumer of biomass, adding CCS to bioenergy solutions (bio-CCS) would enable removal of CO_2 from the atmosphere. CCS is the only technology that can significantly reduce CO_2 emissions – typically by 90% – not only from power plants but carbon intensive industry as well, such as oil refining and steel manufacturing. Finding CCS solutions for heavy industry is therefore important for reducing CO_2 emissions from the Finnish industry.

For the Finnish technology developers and providers CCS could provide a significant market share in the future. Chemical looping combustion (CLC) is a new CCS technology that benefits from Finnish expertise in fluidized bed boiler. Monitoring technologies is another Finnish expertise that can help making CCS a safe and secure emission reduction and improve the social acceptance of CCS.

Mapping the geological storage potential in areas close to Finland is important, as the Finnish bedrock does not have any formations suitable for underground storage of CO_2. However, Finland has also large reserves of minerals that could be used for converting CO_2 into inert carbonate minerals. To enable this, the technology for mineral carbonation needs to be developed further.

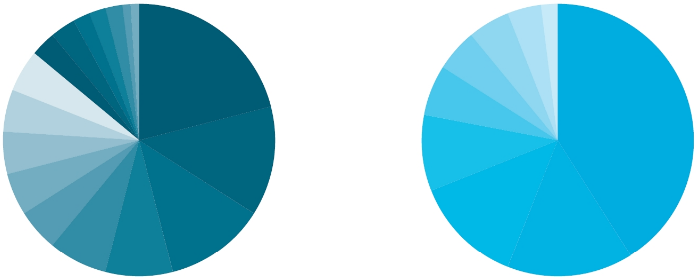
1.2 Overview of CCSP

Cleen Ltd.'s Carbon Capture and Storage R&D program (CCSP) has been prepared for strengthening the position of Finnish industry and research organisations in the CCS technology field and aims for a leading position in certain selected fields of CCS. The objective for CCSP is to develop CCS-related technologies and concepts, leading to essential pilots and demonstrations by the end of the program. A further objective is to create a strong scientific basis for the development of CCS technology, concepts and frameworks, and to establish active, international CCS co-operation.

The program consortium consists of leading research organisations and industry having significant background and references in their own field related to the CCS chain. The consortium consists of 9 research organisations and 17 industrial partners. The budget for the first three years of the program has been about 3 million euro per year.

Main research areas are:

- CCS concepts
  - Solutions for combined heat and power (CHP) plants, multi-fuel power plants, bio-CCS, and heavy industry
  - CO_2 utilisation and novel concepts
- Long-term breakthrough technologies
  - Chemical looping combustion (CLC)
  - Mineral carbonation
  - New concepts
- Monitoring technology
  - Development of methods and technology for monitoring of CO_2 capture and storage
- Framework for CCS
  - Regulation and legislation issues
  - Sustainability and public acceptance of CCS
  - Infrastructure and CO_2 storage capacity.



Industrial partners 52,4%
Fortum Oyj 23%, Ramboll Finland Oy 13%, Vibrometric Oy 12%, Helsingin Energia 8%, Gasum Oy 7%, Neste Oil Oyj 5%, Foster Wheeler Energia Oy 5%, Ruukki Metals Oy 5%, Neste Jacobs Oy 5%, Fortum Power and Heat Oy 5%, Stora Enso Oyj 3%, ÅF-Consult Oy 3%, Oulun Energia 2%, Tapojärvi Oy 2%, Nordkalk Oy Ab 2%, Andritz Oy 1%, Outotec Oyj 1%

Research partners 47.6%
VTT Technical Research Centre of Finland 41%, Aalto University 15%, Lappeenranta University of Technology 13%, Geological Survey of Finland 9%, Tampere University of Technology 6%, University of Oulu 5%, Åbo Akademi University 5%, University of Tampere 4%, Finnish Environment Institute 2%

Figure 2. Budget share of industrial partners and research partners participating in CCSP.

The CCSP program runs from 2011 to 2015 and has an annual budget of 3 M€, with Tekes – the Finnish Funding Agency for Technology and Innovation providing the main part of the funding. The CCSP consortium consists of 17 industrial partners and 9 research partners (Figure 2). The CCSP consortium is managed by Cleen Ltd. – the strategic research centre for the Energy and Environment Cluster.

So far, the program has produced 13 international journal articles, 29 conference articles, 1 Ph.D. Theses, 14 Master's Theses and over 70 internal technical reports.

1.3 International collaboration in CCSP

A specific feature of the CCSP program is an active international networking and collaboration. One significant task of the programme is information transmission and collaboration between national and international actors. Participation and work in several international networks is funded via CCSP, such as IEAGHG (The IEA Greenhouse Gas R&D Programme), ZEP (The European Technology Platform for Zero Emission Fossil Fuel Power Plants), EERA (European Energy Research Alliance, CCS programme), networks of geological surveys (CGS Europe and ENeRG), IGU (International Gas Union) and EASAC (The European Academies Science Advisory Council).

CCSP has an active collaboration with the Swedish CCS project, in particular regarding the mutual Bastor-project. The Bastor-project was established by the CCSP program and the Swedish CCS project. The implementation of the project is done in tight collaboration between Finland and Sweden and all the results are shared. In addition to Finland and Sweden the Bastor-project has established good contacts to several other Baltic Sea countries and thus the project is in practice a multinational activity.

CCSP also collaborates with NORDICCS, a virtual CCS networking platform aiming for increased CCS deployment in the five Nordic countries, by organising joint workshops and seminars.

In addition to the collaboration listed here, the CCSP partners are also involved in other international collaboration activities with significant CCS activities, such as collaboration with the IEA CCS unit, Global CCS Institute, PRISMA, Tekes/A*Star Singapore cooperation, SINTEF and EU projects such as MUSTANG and FLEXIBURN.

2. CCS concept studies

Capture systems for heat and power production and in industrial processes can be very different and specific for each case. Each plant type needs particular concepts, processes, models and studies. In CCSP target is to find optimal CCS application concepts for combined heat and power (CHP) plants and concepts for heavy industries as these are among the largest point sources of CO_2 emissions in Finland (Figure 3). CCS is one of the few technological options available for energy intensive industry to reduce their carbon footprint. In addition to concept studies for CHP production and industrial processes, a systematic innovation process is being employed for finding new low-cost CCS concepts.

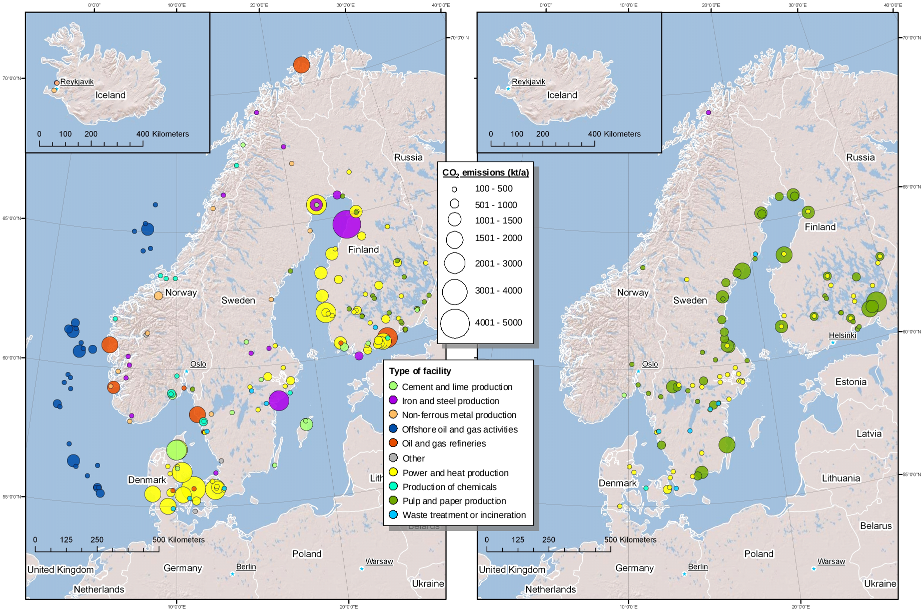


Figure 3. Maps over CO_2 emissions from facilities emitting > 0.1 Mt CO_2/a in the Nordic countries in 2007 (left: fossil and inorganic CO_2 emissions; right: biogenic CO_2 emissions) (Teir et al. 2010).

2.1 CCS for Combined Heat and Power (CHP) plants

Identifying influences of CCS integration to CHP systems are essential in the Nordic energy production infrastructure. In CCSP, influences are assessed on plant and system level with the ultimate outcome being the economic feasibility of these greenhouse gas mitigation options. This includes comparison of different carbon capture technologies, differences between fuels and plant types based on process modelling and further evaluation of costs related (investment costs, additional fuel costs and changes in the production costs of electricity and heat).

2.1.1 Oxy combustion based CCS for CHP, case study

A majority of the CCS studies carried out have focused on coal-firing in condensing power plants. Although carbon capture technologies require energy for capture, most of them produce also an excess of low-grade heat, which could be utilized e.g. in district heating. In addition the utilization of biofuels in CCS is a potential pathway to “negative” CO_2 emissions (see Section 2.3). Adapting CCS technology to a CHP plant using biofuels is a concept with a lot of unknown aspects and several opportunities for process integration.

In CCSP, a study is carried out to analyze the optimization and dimensioning criteria of a CHP plant utilizing 1st generation CCS technology – oxy-fuel combustion. The plant concept uses a full-scale oxy-CFB boiler (Circulating Fluidized Bed) and is studied using different fuel bases (varying mixtures of coal, peat, forest residues, wood pellets, etc.), especially focusing in high shares of biomass. The target for the study is also to define the basis for further analyses of effective 2nd generation CCS technologies in a CHP system environment.

The studied technologies were found to have both advantages and disadvantages. Oxy-fuel combustion processes use almost pure oxygen mixed with recycled flue gases as an oxidant instead of air. This excludes nitrogen out of the process and the flue gases consist mainly of CO_2. The advantage of using oxy-fuel combustion is that less energy is required to separate CO_2 from the flue gases. In comparison to conventional power plants the oxy-fuel combustion process requires two essential large-scale components; ASU – Air separation unit for producing pure oxygen and CPU – CO_2 compression and purification unit for converting CO_2 to storable form. The downside of oxy-fuel combustion is the high auxiliary power consumption of these two additional components.

The new oxy-CHP concept was developed and modeled using Fortum’s power plant simulator Solvo® and Fortum’s earlier CCS studies. The plant layout, capacities and fuel distributions were modeled according to the study design figures. The model consists of the components needed to calculate the power plant's energy balance. The additional oxy-fuel combustion components are taken into account; ASU has been created for Solvo® as its own component and the CPU’s electricity consumption has been approximated by a function while the modeled solution is still under development. The target was to utilize the Solvo® model for the following case studies:

- Biofuel shares (min and max)
- Biofuel moisture levels
- Biofuel drying alternative and its effects
- Different district heating and process steam loads (winter and summer).

The results show that oxy-fuel combustion in biofuel CHP production seems to be beneficial due to the high moisture in flue gases. By utilizing the flue gas condenser even 15% increase in district heating power could be achieved. The biofuel share's effect to plant characteristics was also studied. An increase of the biofuel share decreases the power output but increases district heating power and the plant efficiency (Figure 4).

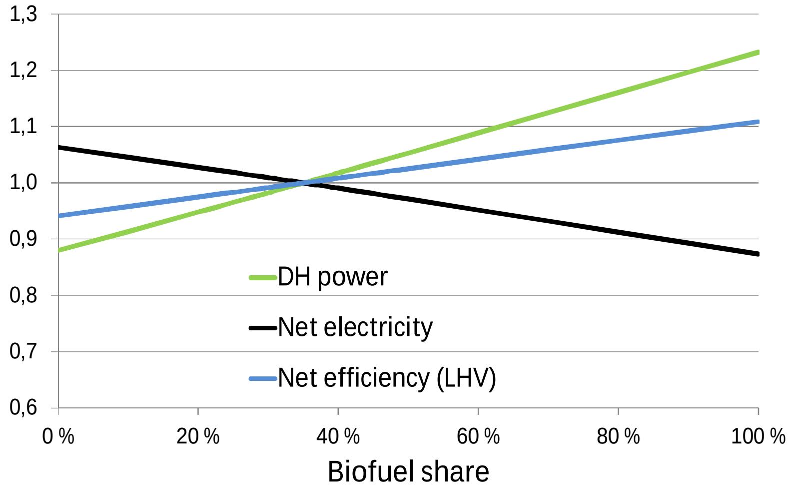


Figure 4. Impact of biofuel share. Reference point at 35% biofuel and 65% coal.

If focusing only on the plant total net efficiency the results are somewhat encouraging, but the power to heat ratio (ratio between produced power and heat) was at the reference point below 0.5. This would cause challenges in summer operation when the heat load is low. The plant produces heat excessively on minimal load. The plant concept would be more profitable if the production would focus more on power production. In the future, the focus will be on studying improvements in power plant operation flexibility. In order to find solution for these challenges technologies such as fuel drying or turbine condensing part will be studied.

A comparison between similar power plants with air and oxygen combustion was also studied. The operational costs of these plants could be determined when the prices of fuels, electricity and district heat were estimated. The preliminary estimations showed that the operation costs of the oxy-fuel combustion concept vs. air combustion are equally economical when costs for CO_2 emissions are on the level of ca. 5–6 €/t CO_2. However, this comparison did not take into account investments or any other variable costs than energy.

In the next phase boiler supplier Foster Wheeler Energia Oy will be involved in the study to integrate the manufacturer aspect to the oxy-firing boiler design and to prepare complete process integrations to the plant concept. Also, the optimization between fuel drying and flue gas condensation will be studied.

Further on there is some process modifications to be considered. The most interesting of these are the effects of implementing a condensing turbine, the optimization of heat recovery systems and alternatives to air purification (major electricity consumer). After studying the alternatives to this plant concept a comparison between other CCS technologies should be conducted.

2.1.2 CCS in gas turbine power plants

Application of CCS technologies to gas turbine solutions is of special interest. Different technical CCS solutions that could be applied to gas turbine installations include pre- and post-combustion technologies, chemical looping, and carbon capture from biogas plants (biogas upgrading). The focus is on finding optimal technological solutions for combined cycle gas turbine (CCGT) plants including specifications for process modelling and possible case studies.

The effect of carbon dioxide capture and storage on the CCGT power plant with combined heat and power was evaluated by two concept studies. Both thermodynamics and cost effects were investigated for a retrofit CCS unit, combined to an existing power plant (Laine 2011), and for a greenfield power plant with CCS (Pirhonen 2011). To determine the impacts of CCS, models of the power plant were created and operation of the power plants with and without CCS was simulated.

The removal and compression of carbon dioxide from flue gases (post-combustion capture) was the only considered option for retrofitting a carbon capture unit into an existing power plant. Chemical absorption with aqueous monoethanolamine (MEA) was chosen as solvent for the capture plant. The carbon dioxide capture plant and compression unit were integrated into the power plant in order to minimise changes required to the existing power plant process. The overall efficiency decreased depending on the mode of operation 15–17%€/-units (Table 1). The results showed that the CO_2 emission allowance price should be over 57 €/t CO_2 to make the investment feasible (Laine 2011).

Table 1. A summary of the results from the studies of combined cycle gas turbine power plant with and without CCS (Laine 2011, Pirhonen 2011).

	Greenfield (pre-combustion)		**Retrofit[1] (post-combustion)**	
CCS	Without	With	Without	With
Thermal energy of natural gas (LHV, MWth)	841	1003	919	919
Net electrical efficiency (%)	48	42	46	40
Overall plant efficiency (%)	89	78	90	74

[1] Mixed mode of operation

Pre-combustion capture technology was found to be the most promising for the greenfield power plant (Pirhonen 2011). The chosen pre-combustion technology consisted of natural gas reforming, a water-gas shift (WGS) process and a CO_2 capture unit placed before the power plant in order to separate CO_2 from the gas before combustion. Chemical absorption with aqueous mixture of methyldiethanolamine (MDEA) and diethanolamine (DEA) was chosen as solvent for CO_2 removal (Pirhonen 2011). The process steam generation was highly integrated between the heat recovery steam generator (HRSG), reforming and WGS sections (Figure 5). The results showed that the efficiency of the power plant with CCS capture was 11%€/ units lower than the corresponding power plant without carbon capture (Table 1). To cover the costs of the plant the price for CO_2 emission allowances need to be at least 80 €/t CO_2 (Siitonen & Pirhonen 2012).

In order to improve the feasibility of the greenfield power plant concept, the following modification options were identified: excluding the pre-reformer, the use of oxygen instead of air in the autothermal reactor (ATR), excluding the low-temperature WGS reactor, and using physical absorption instead of chemical absorption (Figure 5). The most potential options identified were to exclude the pre-reformer and low-temperature WGS reactor (Figure 6), thus decreasing the total plant investment costs by 8% without having any significant effect on the efficiency of the plant. The pre-reformer was considered unnecessary, since the natural gas used in this case contains only minor amounts of heavier hydrocarbons. However, excluding the low-temperature WGS reactor reduced the total carbon capture efficiency from the base case of 90% to 79% (Suomalainen et al. 2013).

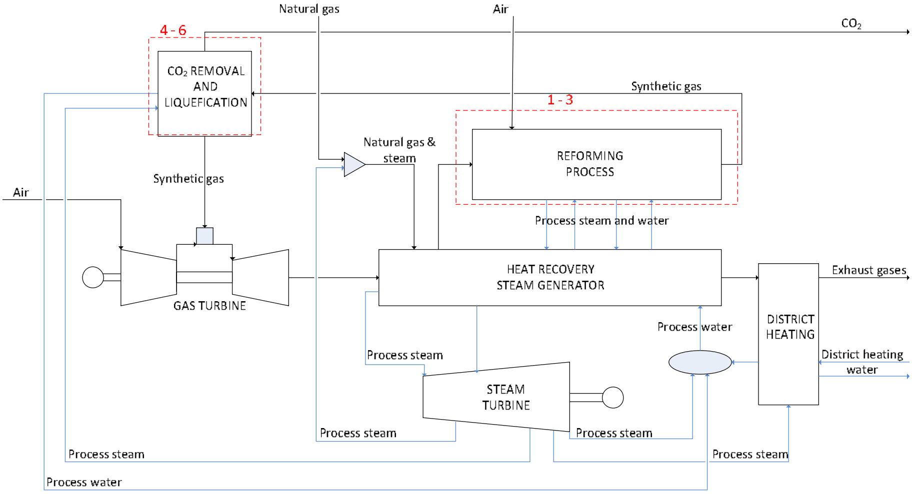


Figure 5. Simplified flow sheet of the natural gas-fired CHP plant using pre-combustion technology for CCS (potential modification options numbered and marked in red) (Suomalainen et al. 2013).

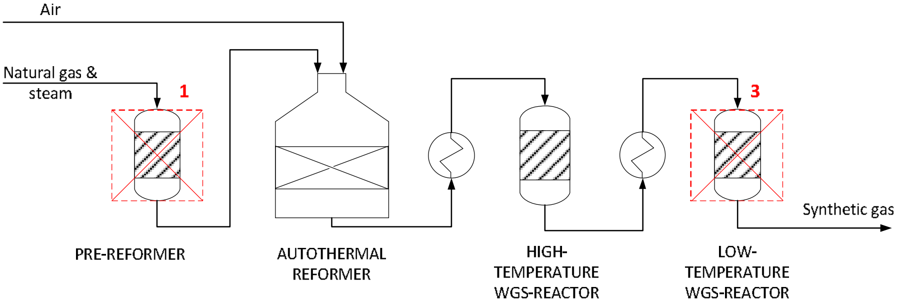


Figure 6. Selected modifications for the reforming process (Suomalainen et al. 2013).

2.1.3 CCS feasibility improvement in industrial and municipal CHP systems

In CCSP, VTT has conducted several conceptual case studies on techno-economic feasibility for industrial and municipal applications. In these studies, the effects of CCS on the local CHP systems are included within the studied system boundaries in order to evaluate the economics and emissions from investor's (local energy company) point of view. The effect of CCS on greenhouse gas (GHG) emissions and operation economics of the CCS cases are compared to the reference systems with varying parameters of operation. Regarding the GHG emissions, besides the site emissions, the main effects on global GHG emissions are also taken into account by using system modelling and streamlined LCA. In the case studies the whole CCS chain, including CO_2 capture, processing, transport and storage are included.

One important task has been analysing the potential for improved plant economics by heat utilisation within the concept studies. A recent paper (Kärki et al. 2013) summarises implications of applying CCS in combined heat and power (CHP) production and in steel industry through three case study approaches conducted in Finland.

The first presented application was a greenfield about 500 MW_{fuel} CHP plant with oxy-fuel CFB-boiler, the second retrofit of about 1000 MW_{fuel} natural gas fired GTCC plant with post combustion capture technology and the third an integrated steel mill retrofitted for post combustion capture. In the paper the effect of CCS on greenhouse gas (GHG) emissions and operation economics of the plants were evaluated with varying parameters of plant operation and market conditions.

The results showed that utilisation of low temperature process heat from capture plant, air separation unit or CO_2 compression in district heating system and/or industrial solutions may offer significant potential to increase overall efficiency and feasibility of CCS processes, especially in the case of oxy-fuel. However, the feasibility of CCS is heavily dependent not only on the characteristics of the facility and the operational environment but also on the chosen system boundaries and assumptions.

2.2 CCS in oil refining

One of the tasks of CCSP is to find CCS solutions suitable for oil refineries. In order to identify different CCS solutions for oil refineries, the CO_2 containing gas streams were first identified and their potential for CO_2 capture evaluated (Lampinen 2012). The off-gas streams of hydrogen production was found to be the most potential streams, while certain combustion flue gas streams were also found to have some potential. The gas streams in hydrogen production are an attractive target for CO_2 capture due to their high CO_2 concentration and the low number and level of impurities. Hydrogen production via steam reforming or with a gasifier can account for 20% of the CO_2 emissions from a refinery. In a medium size oil refinery, with annual CO_2 emission about 3 Mt, this amounts to about 0.6 Mt of CO_2 per year.

Different carbon capture technologies suitable for steam methane reforming (SMR) plants producing hydrogen were compared (Andtsjö 2013). Technology alternatives were screened for two gas streams: the off-gas from hydrogen purification, and the flue gas from the SMR unit’s furnace. After the evaluation of the technology alternatives, the applicability of a cryogenic capture process to both streams was selected for an engineering analysis. Also, the technical applicability, investment cost and operating costs were estimated. It was concluded, that the most attractive stream in SMR hydrogen production to be used for carbon capture is the off-gas from hydrogen purification. Between the two analysed gas flows, the hydrogen purification off-gas was economically clearly more competitive than the flue gas. For CO_2 capture from the flue gas, the cryogenic process was found to be less feasible than amine absorption. Regarding the SMR hydrogen purification off-gas, the combined cryogenic and methanol absorption process was found to be economically more advantageous compared to the analysed cryogenic process. The estimated production cost for captured CO_2 was in all cases clearly higher than the present emission allowance cost of CO_2 (Andtsjö 2013).

2.3 Bio-CCS as a carbon-negative solution

The need for carbon-negative solutions as safeguards against irreversible climate change is increasingly being recognized on an international level. Biomass with Carbon Capture and Storage (Bio-CCS) has the potential as a carbon negative solution against climate change; contributions that are increasingly likely to become indispensable. Lately, Bio-CCS has started to receive a lot interest, especially in Europe where the expansion of renewable energy is high on the agenda with the 20-20-20 targets.

Finland and Sweden have large biogenic CO_2 emissions, mostly from pulp and paper industry and from power plants co-combustion biomass (Figure 3). Photosynthesis binds carbon from the atmosphere and the carbon is again released during biomass combustion, making the process carbon neutral. Capturing and permanently storing biogenic CO_2 emissions from these processes would thus lead to net negative emissions and therefore create a carbon sink.

A report on Bio-CCS was recently published by the European Biofuels Technology Platform and Zero Emissions Platform with a significant contribution from VTT through CCSP (EBTP & ZEP 2012). The report concludes that Bio-CCS and negative emissions can make a significant contribution to climate change mitigation and that Bio-CCS is currently the only large-scale technology that can remove CO_2 from the atmosphere. Liquid biofuels production may be an appealing target for deployment with near-pure CO_2 streams but as with all bio-based production, the utilization of a constrained resource must be taken into account; is CCS adding significant value (economic, GHG reduction, public perception) to certain biomass utilization technologies and therefore should the biomass utilization be directed accordingly? Generally the same technologies considered for capturing of fossil CO_2 could be applied for biomass based processes as well. The main differences and restrictions are mainly related to shares of biomass in co-firing, regional availability, typical sizes of installations and availability of sustainable raw material. Current policies for lowering greenhouse gas emissions do not recognise negative emissions from power plants, and thus no fiscal incentive exists for capturing CO_2 from biomass installations. To make Bio-CCS deployment happen in Europe, biogenic CO_2 emissions must be acknowledged, and carbon-negative solutions must be incentivized in the EU ETS.

A Bio-CCS roadmap for Finland is currently under construction in CCSP. The objective of the roadmap work is to understand the complexity of the issue and to get a realistic estimate how big contribution these Bio-CCS technologies actually could provide. The underlying question for a country with biomass resources available is: what is the best way of utilizing the constrained biomass resources. Constructing this Bio-CCS roadmap for Finland is based on existing infrastructure, sustainable resource potential, prices and national targets. Sectors considered are power production (condensing and CHP), pulp and paper, iron and steel, liquid biofuels production and oil refining with technologies related.

A toolkit for economic evaluations of CHP plant operation has been prepared on issues related to Bio-CCS. The toolkit provides scenarios for dedicated biomass, multifuel (50/50 bio-peat) and dedicated peat fired plants with selectable user input parameters. Comparison of oxy-fired CFB plant and normal air-fired CFB plant is in the focus to provide information on CCS feasibility. The toolkit available here: http://virtual.vtt.fi/virtual/combust. More info about the conducted case studies can be found in Tsupari et al. (2011).

2.4 CCS in steel industry

Iron and steel industry is a significant sector contributing globally to about 6% of anthropogenic CO_2 emissions from energy use (IEAGHG, 2011). Carbon capture and storage is the only widely applicable solution to significantly reduce the CO_2 emissions from iron and steel sector, which is largely relying on the blast furnace-based steel production route.

In CCSP, new process concepts suitable for application in Finnish iron and steel industry has been identified and evaluated. Technologies under more detailed evaluation for capturing carbon dioxide from steelmaking processes are post-combustion capture and oxygen blast furnace technologies. Various technical solutions, technologies and integration configurations have been evaluated for these. For example, three different solvent options for post-combustion capture and two different CO_2 reduction scenarios for oxygen blast furnace process have been analysed. With these processes about 1–3 Mt CO_2/a can be reduced on studied iron and steel mill, accounting for approximately 25–75% of the whole site emissions. Investigation of greater emission reductions with these technologies is not relevant, as at integrated steel mill, CO_2 emission sources are scattered around the large industrial site and the flue gases are led to several stacks.

Application of post combustion carbon capture on an existing steel mill is relatively simple in comparison to the extensive process modifications required in the case of oxygen blast furnace (Arasto et al. 2013b). Consequently, the impacts of using an oxygen blast furnace are more diverse as, for example, LPG consumption and electricity purchase will be increased, but significant economic savings are achievable since the coke consumption is reduced. Thus, the oxygen blast furnace also enables a wider range of process optimisation to suit very different operational and economical environments. This is reflected for example with the fact that the sensitivity of the feasibility of the oxygen blast furnace process for the electricity price is higher than in the reference case or with post combustion carbon capture. In other words if the electricity prices rise, the feasibility of carbon capture with an oxygen blast furnace decreases more than the feasibility of post combustion carbon capture. This includes high risk as the CO_2 allowance price penetration to the electricity market price is of significance. However, the cost of globally avoided emissions is heavily dependent on the assumed type of substitutive electricity generation and substitutive fuel usage (Tsupari et al. 2013).

In recent studies, different possibilities and the feasibility of applying carbon capture at an integrated steel mill based on blast furnace process were studied (Arasto et al. 2013a & 2013b). Implications of different capture amounts, different solvents for post-combustion capture and process integration levels to the greenhouse gas balance and operation economics were compared to the base case for steel production. Furthermore the effect of reducing the carbon intensity of steel production on the final steel production cost was evaluated. The assessment was based on a case study on Ruukki Metals Oy’s steel mill in Raahe. The mill is situated on the north-eastern coast of the Gulf of Bothnia, emitting approximately 4 Mt of CO_2/year. Due to the location of the installation only ship transportation of CO_2 is considered. Carbon capture processes and process integration options were modelled using Aspen Plus and the results were used to estimate CO_2 emission reduction possibilities and carbon abatement costs from an investor's point of view. Different heat integration options and heat utilization scenarios were investigated and optimized with a custom-built CC-Skynet™ economics toolkit. Also, different technologies related to oxygen blast furnace were considered, both for oxygen production and for top gas treatment. With a whole chain approach, including CO_2 capture, processing, transport and storage, the results showed a significant reduction potential: up to 2.9 Mt/a using CCS. The cost breakeven point, i.e. when CCS turns more feasible than buying carbon credits in the reference case, for the plant owner were in the range of 50–90 €/t CO_2, for most of the considered cases. However, the breakeven prices are very sensitive for electricity prices (Figure 7). Typically the breakeven prices in steel industry seem to be somewhat lower than in most of the cases evaluated for other Finnish CCS applications, e.g. power plants. In addition, several potential ideas for further optimisation were identified during the work.

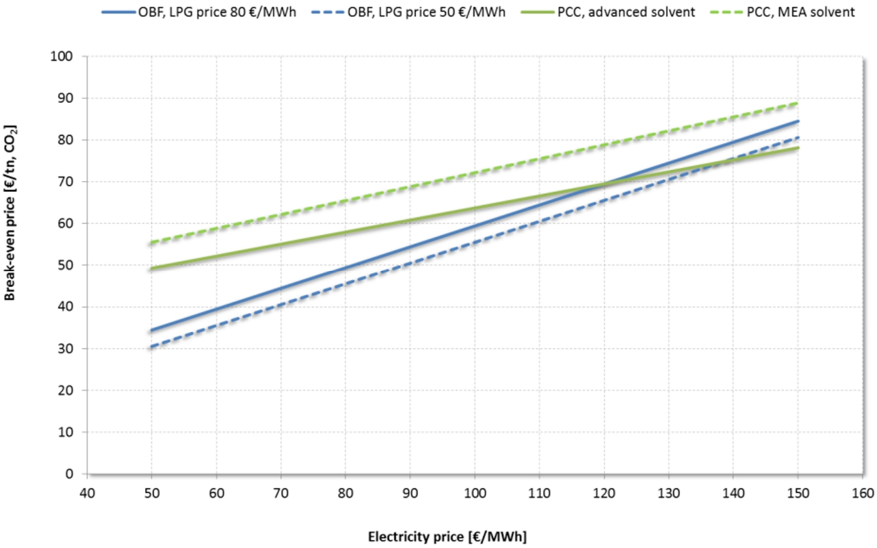


Figure 7. Low-cost scenario example of the effect of electricity price to the break-even price (i.e. the price of emissions allowances needed to motivate CO_2 capture instead of buying CO_2 emission allowances) from the operator's point of view.

International co-operation with ZEP other industries WG, EERA CCS JP, IEA GHG Programme projects and especially MEFOS and ULCOS II projects regarding Oxygen Blast Furnace have been of significant importance for the succession of the work. The intermediate results of the task have had a strong international visibility among research community working on CCS in industry and the policy makers in Europe.

3. Development of monitoring technology

When a new technology, as amine-based CO_2 capture plants (Figure 8) or geological storage facilities, is deployed on a large scale the risks have to be fully managed. If not, a promising or even good technology may encounter backlash and fall under social pressure, even if the problems would be solved later. Reliable measurement technologies are necessary for proving the maturity of the technology and develop the process to the safe level.

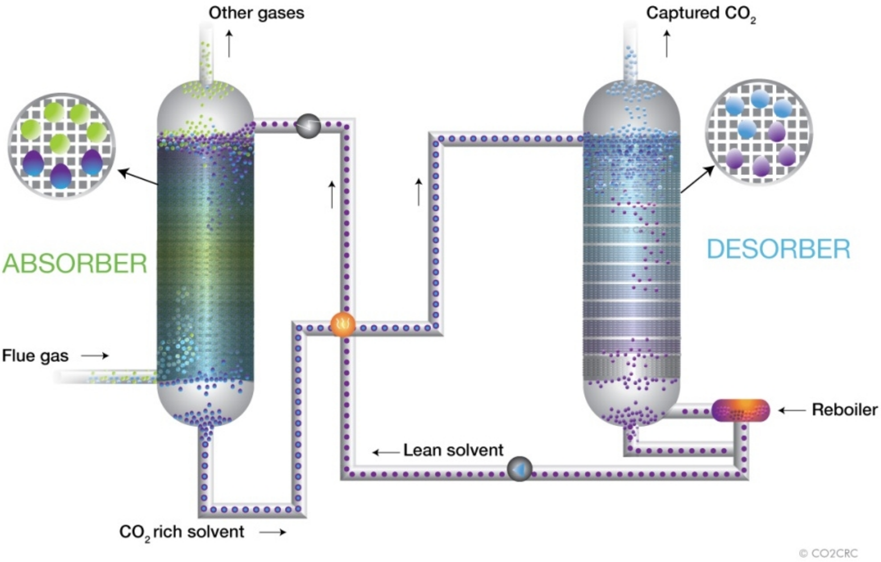


Figure 8. Principle of an amine based CO_2 capture process.

A carbon capture process is not enclosed (see, for instance, Figure 8), which means that the process causes emissions that will be dispersed into the environment. The amount and quality are related to the used capture technology, but also depending on how the process is implemented. Chilled ammonia and amine-based solvents are the most studied technologies and especially amines are proved to degrade in the process forming potentially harmful components, while ammonia processes produces mainly ammonia slip. As solvent amines are typically non-harmful the focus has been drawn into some selected degradation products, of which some, such as nitrosoamines, has proven to be carcinogenic.

In the other end of the CCS chain, successful long-term storage of CO_2 in underground formations requires also various monitoring technologies. The structural geometry and flow pathways of the considered rock formation need to be surveyed using various tools for seismic survey. Furthermore, monitoring is required to verify that the CO_2 remains in the rock formation long after the injection has stopped. Possible monitoring techniques for future CO_2 storage facilities include atmospheric monitoring, soil gas and water sampling and seismic surveys (Figure 9).

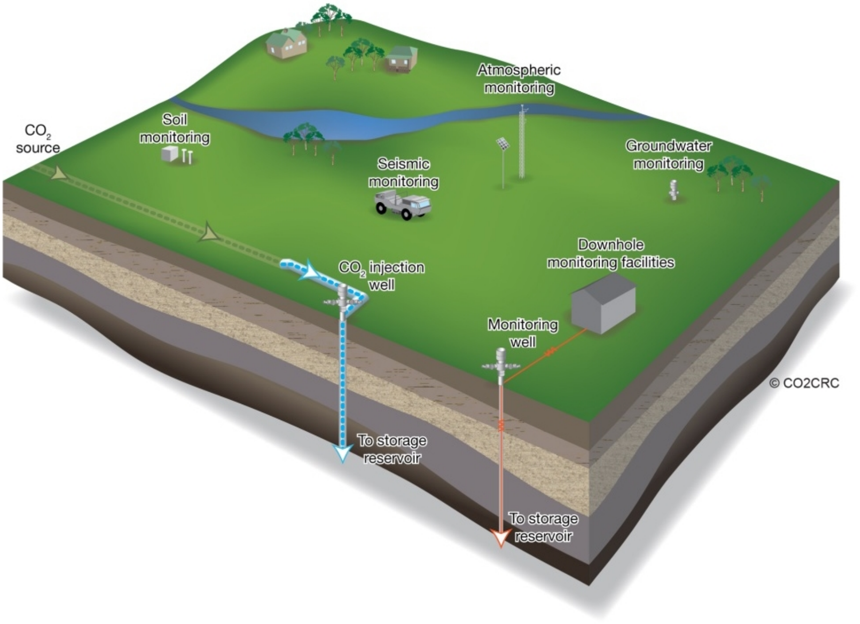


Figure 9. Monitoring techniques for CO_2 storage include atmospheric monitoring, soil gas and water sampling and seismic surveys.

3.1 Monitoring of emissions from CO_2 capture processes

In CCSP, Ramboll Oy started studies related to emissions of ammonia and amine based processes. It was soon apparent that standard sampling or analysis methods for potential emission compounds from these processes were not available. N-nitrosoamines was found to be most significant compound group what comes to environmental issues from post combustion amine plant. The main focus has therefore been on developing robust and reliable nitrosoamine detection methods.

During the program several different analysis methods have been established. A couple of common CO_2 capture absorption solvents have been used as a synthetic matrix and methods have been developed accordingly. The main solvent in the tests has been monoethanolamine (MEA). Methods have been developed for several different matrices such as:

- Pure water representing drinking water
- Washer section water representing flue gas condensate and flue gas washing phase
- Solvents representing samples taken from the CO_2 capture solvent
- Absorption medium commercial cartridges, absorption liquids on flue gas sampling.

In case of MEA one of these nitrosoamines is N-nitrosodiethanolamine (NDELA). It was observed, that NDELA is both important to analyse and difficult to be separated from the solvent matrix. Development of sampling and analytical methods was started for selected compound groups: alkylamines, solvent amines, nitrosoamines, aldehydes and ammonia. Key challenges were to develop methods allowing for separation of chemically similar compounds from each other and offering detection limits in the order of ng to µg per liter.

A method for the analysis of seven common nitrosoamines described in United States Environmental Protection Agency (EPA) method 521 (Munch & Bassett 2004) and an MEA matrix up to 30 per cent has been successfully developed. With sophisticated mass spectrometers, detection limits under 1 µg/l has been achieved. Finally, a partially working analysis method for the NDELA was established. However, the method is totally different approach compared to the EPA 521 method, and further development is needed. The methods were developed for all the matrices described above. Moreover, nitrozation prevention practises were established. In addition, methods were developed for 12 carbonyl compounds (mainly aldehydes). The methods are based on derivatization with DNPH. Methods for the selected alkylamines and MEA were also developed.

A prototype for the sampling train for flue gas sampling was established. Isokinetic sampling (sampling velocity the same as the flue gas velocity) should be applied due to high water concentration. Unfortunately, most of the compound groups need a different approach. Methods for the work hygienic purposes were also established for some compound groups.

In 2012, Ramboll established a Round-Robin comparison tests for four different international laboratories involved with analysis of emissions from CO_2 capture plants. The results showed that Ramboll has established methods which are relevant and comparable with the other laboratories in the field, but with lower detection limits. This has gained interest within foreign operators and designers working with CO_2 capture. Based on development and validation work done and round robin test arranged in CCSP, Ramboll got sufficient evidence for requesting accreditation for EPA 521 N-nitrosoamines measurement from CO_2 capture solvents.

In the evaluation by FINAS (Finnish Accreditation Service) the method was approved and Ramboll possesses now one of the first accreditations for this compound group in the world.

3.2 Seismic characterisation and monitoring of CO_2 storage

Seismic investigations, including those performed in boreholes, have proven useful for choosing suitable storage formations and for monitoring the evolution with time of the injected CO_2. Without this information it is difficult to assess the CO_2 plume position, monitor its extension and interaction with the host formation, or predict its evolution, including potential migration to adjacent formations. The seismic data collection and processing methods are being improved and new technologies developed in order to make geologic CO_2 storage as efficient and safe as possible. Seismic monitoring of a CO_2 plume extension is commonly performed by 3D seismic surveys performed from surface (Figure 10, left-hand image). The main advantage of surface methods is the wide coverage of the site from above, which allows the horizontal extension of the plume to be imaged. The resolution can however suffer because of the large distance from the surface to the reservoir. Borehole seismic studies (Figure 10, right-hand image) were less used in the past, partly because of logistic difficulties with setting up frequent surveys in boreholes in the presence of CO_2. Such difficulties are currently addressed by developing seismic receivers and sources for boreholes, which would allow the plume to be monitored permanently, from its proximity.

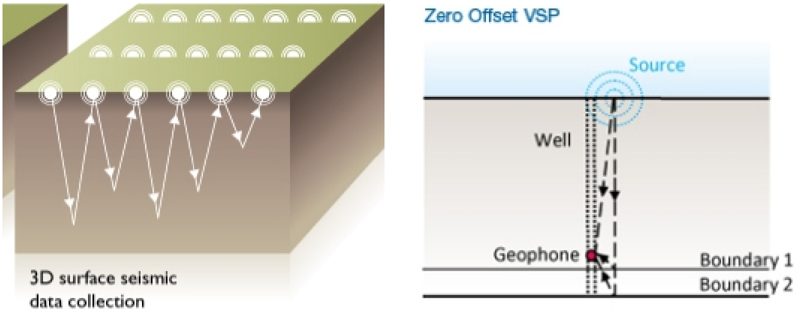


Figure 10. Difference between seismic surveys taken from the surface (left) or using a borehole (right) (Images © CO2CRC).

In CCSP, Vibrometric Oy focuses is on developing seismic characterization and monitoring techniques, which are necessary for the adequate understanding of the structural geometry and flow pathways of potential geologic CO_2 storage formations.

Seismic data was collected in two CCS EU projects, CO2SINK and MUSTANG. The data were analysed as a means of testing the methods and techniques being developed in CCSP. These include time-lapse VSP (Vertical Seismic Profiling) with its variant MSP (Moving Source Profiling) and time-lapse seismic cross-hole data sets. The development was aimed at improving the resolution reliability and efficiency of the methodology currently used for CCS seismic investigations and at designing and building acquisition tools that meet the specific requirements of CCS seismic monitoring.

An integrative concept was applied at the Ketzin CO_2 injection test site, Germany, where a comprehensive seismic monitoring program has been unrolling for more than 5 years. Seismic monitoring comprised baseline and repeat observations at different scales in time and space: surface 3D and multi-line 2D, VSP (Vertical Seismic Profiling), MSP (Moving Source Profiling) and cross-well seismics. It was found that VSP/MSP time-lapse surveys can monitor the evolution of the CO_2 plume accurately and in a timely manner. The reservoir layer can be imaged with higher resolution than from surface, while the coverage is limited to the vicinity of the observation well, to a cylinder with a radius of app. 300–500 m (in this case the restriction is mainly due to the acquisition geometry). Cross-well measurements cover the smallest scale, between wells ~100 m apart but are capable of detecting very small CO_2 amounts, therefore may be useful for identifying unpredicted CO_2 migration (leaks).

Furthermore, a 16-level wide-band 4-component receiver tool for borehole seismic surveys at CO_2 storage sites was developed by Vibrometric for measurements at depths of 1.6 to 2 km. The frequency band of the instrument was extended downwards to 1 Hz. In-situ evaluations were done at the Heletz CO_2 injection site (Israel), as a part of the EU funded MUSTANG project. Test records are currently being evaluated.

The development of test instruments and procedures in CCSP is being continued. One priority is to extend the frequency band for both seismic sources and receivers. Modelling results undertaken in this program show that by using lower frequencies than usually obtainable by reflection seismic equipment it may be possible to reduce the number of source and receiver points for monitoring CO_2 geological storage sites. However, the capability of producing and recording high frequencies should also be conserved for detailed monitoring whenever possible.

4. Capture of CO_2

Various technical solutions exist for capturing CO_2 before or after combustion (or conversion, in case of certain industry processes). Some capture processes are already in use by industry for producing CO_2 for industrial use. However, this production is in a relatively small scale as compared to the millions tons per year needed for a capture unit in a full-scale CCS power plant. Several new capture methods are in different stages of development. These are being studied in CCSP with a special interest in oxy-fuel related technologies and biofuel solutions.

Cost-effective carbon capture technologies are still not commercially available for large-scale implementation on power plants. Technologies that are the most mature ones include Fluor’s Econamine FG+, Mitsubishi Heavy Industries KM CDR, Hitachi H3, Cansolv Technologies, Aker Clean Carbon and Alstom's Chilled Ammonia Process (ACAP). These technologies have been tested at scales on slip streams no larger than 1–40 MWe from coal-fired power plants, the size of a typical coal-fired power plant being 500 MWe.

Most of the capture technologies in development face the following issues:

1. They have not been successfully demonstrated at the scale necessary for power plants;
2. The parasitic loads (both steam and power) required to support CO_2 capture significantly decrease power generating capacity and require more fuel input to produce the same power output; and
3. They are not cost-effective.

Other separation methods such as membranes and chemical looping combustion are being considered as a potential technology that could be employed at a later stage, since these are not as mature as the main carbon capture technologies based on absorption or oxy-fuel combustion. In CCSP, chemical looping combustion has been selected for further development as it benefits from the Finnish expertise in fluidized bed combustion technology.

4.1 Oxy-fuel combustion

Oxy-fuel combustion in circulating fluidized bed (CFB) boilers is a CCS technology area where Finnish technology providers are world-leading. Understanding the technical challenges and limitations of oxy-fuel combustion as well as the related cost structures for fossil, biomass and co-firing cases is essential for several actors in Finland. In CCSP, the focus has therefore been on further developing models and modelling tools for increasing the understanding of various processes related to oxy-fuel combustion in CFB boilers. As part of this work flexible simulation environments are being developed. In order to understand the phenomena and limitations of oxy-fuel combustion boilers, combustor process models for air-firing are further developed and updated to provide estimates for combustion, heat transfer, fluid flow and emission performance under various oxy-fuel combustion conditions. This allows for more accurate unit processes to be utilised in process simulators of a wider scope.

A dynamic simulation tool has been developed for concept studies of oxy-fuel CFB processes, consisting of an air separation unit (ASU), a circulating fluidised bed (CFB) boiler island and a CO_2 purification unit (CPU). The simulation tool is needed for studying the dynamic performance of (heavily) integrated processes in oxy-CFB power plants and to develop its control strategies. Different linking techniques to integrate two separate dynamic modelling programs, Aspen Plus Dynamics and Apros, have been evaluated. The reason for integration is to utilise the best features of the simulators: Apros is strong in boiler and turbine processes, and Aspen in distillation processes like air separation and CO_2 liquefaction. The proper method for linking (via Matlab/Simulink) was found, tested and implemented. In addition, the possibility to transform AspenPlus models into AspenDynamics models has been successfully tested.

One particular objective is to develop the knowledge and the modelling capabilities of heat transfer and limestone reactions in CFB boilers in oxy-fuel combustion conditions.

Due to lack of atmospheric nitrogen in oxygen fired combustion, the partial pressures of CO_2 and H_2O in flue gas are substantially higher than in air fired combustion. Both gas species are radiating gases, which affects the radiation heat transfer both in the furnace and in the backpass. In CCSP, the gray and non-gray modelling of radiative heat transfer in a large back pass channel of a CFB boiler have been made using a zone method, which has been developed at LUT (Bordbar & Hyppänen 2013). A comprehensive comparison has been done to determine the accuracy of the gray gas modelling (Figure 11). In addition some analysis has been done to show the effect of combustion types (air/oxy fired) on the overall radiative heat transfer of a backpass channel (Figure 12).

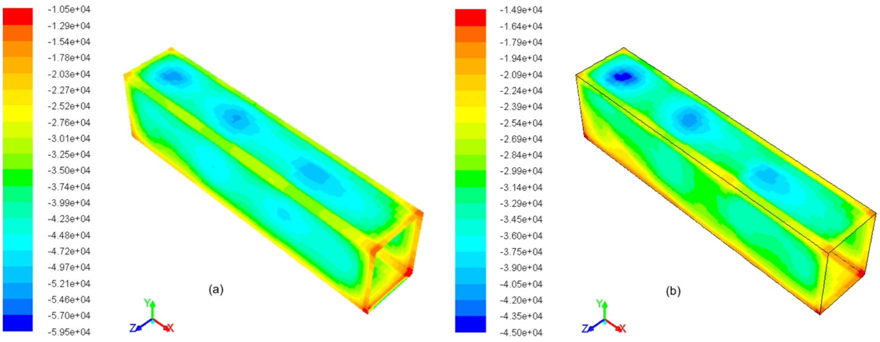


Figure 11. Radiative heat flux (W/m$_2$) in the walls of a backpass channel for the case of oxy-fired combustion; (a) gray modeling, (b) non-gray modeling.

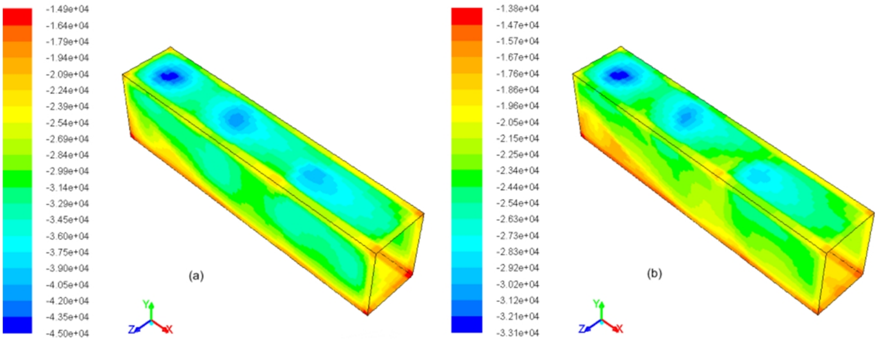


Figure 12. Comparison between the radiative heat flux (W/m^2) calculated by non-gray radiative zonal method for an oxy-fired case (a) and an air-fired case (b).

Using simplified condition for radiative properties of gas particle fluid in the furnace of a CFB boiler, preliminary results of radiation heat transfer modelling has been obtained using the developed zone method. The calculated radiative heat flux in the walls of the selected geometry is shown in Figure 13. The other important information obtained by LUT zonal model is the radiative source term in the volume of the furnace which is shown in Figure 14.

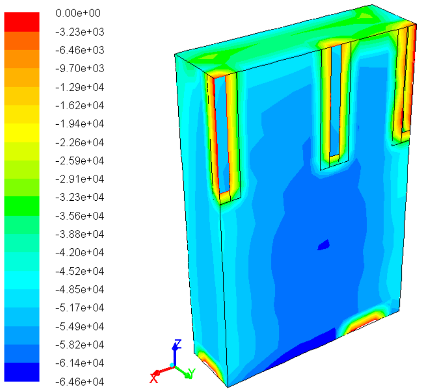


Figure 13. The radiative heat flux (W/m^2) in the solid walls of CFB3D geometry.

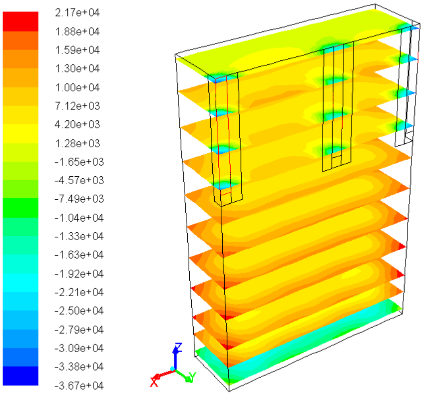


Figure 14. The radiative source term (W/m^3) in several cross sections of the geometry in Z directions.

Another objective is to study limestone reactions in oxy-fuel combustion conditions in CFB boilers and further develop existing particle models. The oxy-fuel combustion conditions can have a great influence on limestone reactions and these effects are not well known. A deeper understanding of these reactions is required for developing the knowledge of reaction phenomena and development of comprehensive oxy-fuel combustion process models. A sub-model of limestone particle model for carbonation has been validated with bench-scale experimental data for the study of non-stationary condition. Limestone reactions in oxygen-fired conditions at different furnace temperatures have been modelled by a steady-state three-dimensional modelling and compared with air-fired combustion (Figure 15, Myöhänen et al. 2013). Particle trajectories in different combustion conditions inside the steady-state 3D model have been determined to produce a gas and temperature history for the particle model. Limestone reactions in these conditions have been studied with the transient particle model (Rahiala et al. 2013).

Future work includes further development of the models presented above.

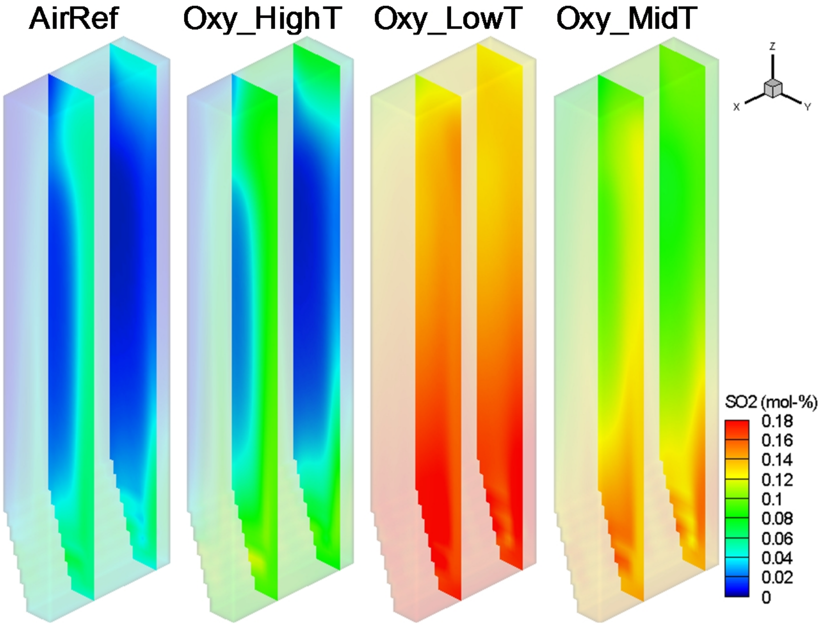


Figure 15. Modelled sulphur dioxide profiles in air-fired (AirRef) and oxygen-fired cases at different temperatures (Myöhänen et al. 2013).

4.2 Post-combustion capture

In post-combustion capture, aqueous alkanolamine solutions are commonly used for removal of acid gases from refinery, flue and natural gas. Primary amines used for gas stream purification are monoethanolamine (MEA), diethanolamine (DEA), methyldiethanolamine (MDEA) and diisopropanolamine (DIPA). In addition, mixtures of the previous ones are also used as aqueous solutions for carbon capture.

Heat stable salts are formed in CO_2 capture processes when oxygen is present in the system. The effects of heat stable salts in CO_2 capture have been investigated in general level, but their effects on phase equilibria have not been studied previously. Heat stable salts are undesirable components in CO_2 recovery systems because they do not regenerate back into alkanolamine in a stripper unit. Thus, heat stable salts tie up the amines at the expense of the amine capacity. Heat stable salts also cause foaming and corrosion in process equipment.

The focus on the work in CCSP is to study heat stable salts effects on CO_2 solubility in aqueous amine solutions. The information of heat stable salts effects on CO_2 solubility is important when CO_2 capture processes have to be modelled accurately.

An expression for the Henry's law constant in aqueous binary and ternary amine solutions has been developed (Penttilä et al. 2011). The Henry's law constant of CO_2 is needed to describe the molecular or physical solubility of CO_2 in aqueous alkanolamine solutions. The model has been developed for the following aqueous amine systems: MEA, DEA, DIPA, MDEA, 2-amino-2-methyl-1-propanol (AMP), MEA+MDEA, MEA+AMP, DEA+MDEA, DEA+AMP, DIPA+MDEA and MDEA+AMP. The Henry's law constant is needed as part of vapour-liquid equilibrium (VLE) models when acid gas is present in the system. The model predicts the Henry's law constant in aqueous binary and ternary amine solutions either comparably or better than the models found in the literature and it behaves consistently on the whole composition and temperature range.

A new model for the density of aqueous DIPA solution has been developed (Uusi-Kyyny et al. 2013). The Redlich-Kister type polynomial has been generally used to describe the densities of aqueous alkanolamine solutions but in case of aqueous DIPA solution the model is not satisfactory. The Redlich-Kister polynomial describes the whole composition range of aqueous DIPA solution but only at one temperature at a time. That means that each temperature needs its own polynomial correlation which is not practical in VLE calculations. Instead, this model is dependent both on temperature and composition of aqueous DIPA solution.

Ionic liquids have traditionally been considered to be non-volatile by having negligible vapour pressure. Therefore, vapour pressure data have only been measured with indirect methods, which mean that the vapour pressure has not been measured but it has been calculated from measured quantities. Only recently, it has been indicated that it is possible to measure vapour pressure data for ionic liquids with direct methods. In the ongoing work at CCSP, pressure data for an ionic liquid/heat stable salt system have been measured successfully by using a vigreaux type distillation column. In addition, a new way to describe the vapour pressure of an ionic liquid/heat stable salt system has been developed. The model is different from the models found in the literature. The new model takes into account the reaction that occurs when 2-(hydroxy) ethylammonium acetate (2-HEAA) dissociates into its initial substances, MEA and acetic acid (HAc), prior to vaporizing in vacuum distillation. 2-HEAA reforms from MEA and HAc when the temperature decreases low enough in the condensing unit. This means that 2-HEAA does not possess vapour pressure in the circumstances used in this work but instead the measured vapour pressure is the vapour pressure of the ionic liquid system.

Densities were measured for the water + 2-HEAA and MEA + 2-HEAA systems and modelled with the Redlich-Kister equation. In addition, solid-liquid equilibrium data were obtained with visual method for two different systems: water + 2-HEAA and MEA + 2-HEAA. The enthalpy of fusion and the melting point of 2-HEAA and of MEA were measured with the Differential Scanning Calorimetry (DSC). The enthalpy of fusion was needed for modelling the SLE data. VLE data were measured for the water + 2-HEAA, HAc + 2-HEAA and MEA + 2-HEAA systems but only the water + 2-HEAA and HAc + 2-HEAA systems were successfully conducted. This information is needed when heat stable salts effects are taken into account in modelling of CO_2 capture.

The work will continue by making the SLE measurements for the HAc + 2-HEAA system. In addition, more vapour pressure data will be measured since the data measured earlier were not satisfactory. When all the measurements have been completed, a scientific article will be prepared from the measured data. One article has already been submitted to the international journal of greenhouse gas control and now it is under review.

For the rest of the program the plan is to measure CO_2 solubility to the salt + water + MEA system and to measure heat of reaction of MEA + HAc with a flow calorimeter. CFD modelling will be completed by implementing a study of the impact of the misdistribution of the vapour phase in the packing efficiency.

4.3 Looping technologies

Chemical looping combustion is a process where oxygen separation is integrated to process itself, using a dual reactor system (Figure 16). The oxygen needed for combustion is fixed to metallic oxygen carrier in the air reactor, after which the solid oxygen carrier is transferred to the fuel reactor. Combustion happens at fuel reactor, resulting in an almost pure gas mixture of carbon dioxide and steam stream. The oxygen carrier is then returned to the air reactor for re-oxidation. This neglects need of air separation unit or post-combustion nitrogen separation.

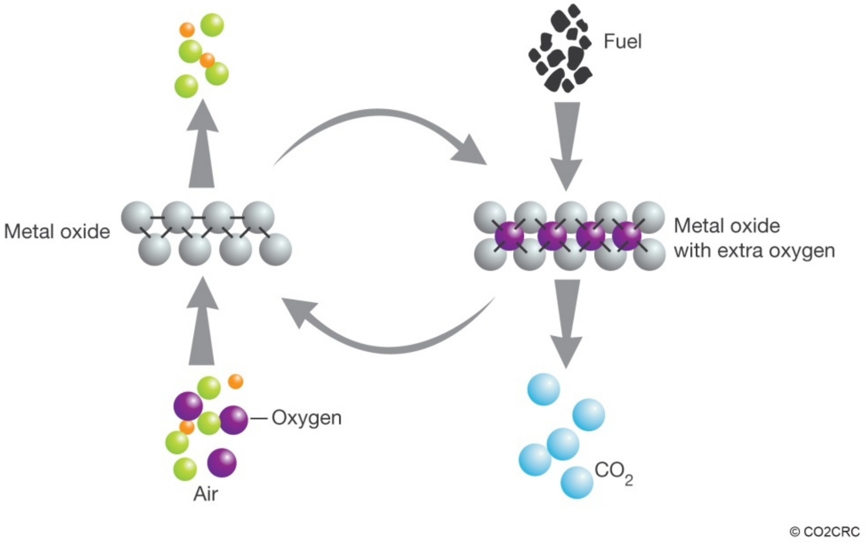


Figure 16. Principle of chemical looping combustion. The left part of the process takes place in the air reactor, while the right part of the process takes place in the fuel reactor.

The potential of CLC in comparison to first generation carbon dioxide capture technologies is high. Ideally, the energy penalty of CLC is around 2.5%-units, which comes mainly from the CO_2 compression, which is low in comparison to the energy penalty for an air separation unit used in oxy-fuel combustion (approx. 7.5%-units).

CLC technology has potential to become a breakthrough CCS technology that would lower the energy penalties and decrease the overall costs of carbon capture. Technology development is still in an early phase after around ten years of research. CLC has been demonstrated in laboratory scale mainly with gaseous fuels. The possibility to apply the technology to solid fossil fuels opens even a greater opportunity to be superior in cost of CO_2 capture and that promising R&D area is very new.

Moving from small scale to commercial unit, typical challenges involve aspects of both physical and chemical nature. Development of various modelling and simulation tools is essential for the design, optimization, and upscaling of the CLC process. This is part of the work done in CCSP.

In order to allow control of the combustion process successfully, the ability to adjust and control the circulation of solid oxygen carrier material is important especially at partial loads. Therefore, laboratory equipment for studying CLC hydrodynamics using a double exit loop-seal has been constructed and hydrodynamic tests have been performed. Oxygen carriers have been produced by using a spray-drying method for testing in a thermogravimetric analyser and fluidized bed conditions. Research shows that hydrodynamics and the handling of solids in the process are essential engineering problems to solve for development of the chemical looping combustion process. The cold model tests show that the concept of two interconnected reactors with two double exit loop-seal can support solid circulation and is adjustable (Tähtinen et al. 2012).

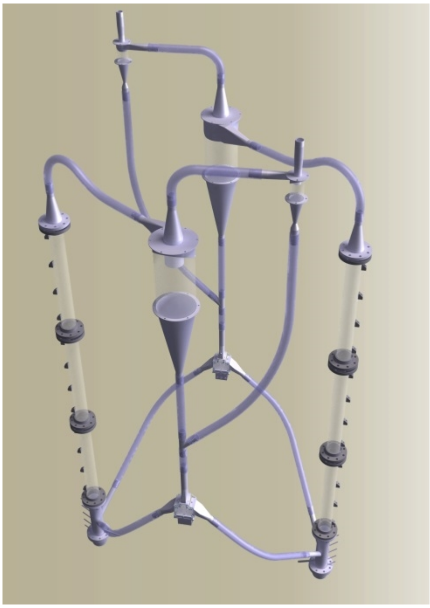


Figure 17. 3D rendered image of the equipment built for solid circulation testing at VTT.

Two simulation tools have been developed: (1) one-dimensional dynamic model for the investigation of a CLC system consisting of two interconnected fluidized bed reactors and (2) a combined CLC–steam power plant model to predict the overall efficiency of the process.

The 1-D model frame can be considered as a state-of-the-art simulation tool for gaseous fuel CLC process giving elaborate information about the complex operation of two interacting fluidized bed reactors (Peltola et al. 2011a, 2011b). As a modelling result, the global solids circulation rate, the conversion of the carrier and the gas composition at the reactor exit can be predicted. Helping to create an optimized reactor design, a variety of 1-D profiles of different parameters (temperature, solids density, gas concentrations, reaction rate, gas and solids velocities etc.) is obtained providing detailed insight into the reactor performance. The 1-D model was validated against the experimental data obtained from a 120 kW CLC pilot unit located at the Vienna University of Technology, and good agreement was observed between the experiments and simulations. Because of the limited practical experience, evaluating the performance of a CLC system on industrial scale is challenging. However, the validated 1-D model offers a great possibility to examine the operation of CLC reactors involved in a large scale process, and the capability to model properly the hydrodynamics, reaction kinetics, and heat transfer of such an intricate system is an important step towards the commercialization of this promising technology for CO_2-free energy production.

With the CLC-steam power plant model, calculation of overall efficiency of different plant configurations, evaluation of design and off-design performance and process optimization with genetic algorithms can be conducted. A case study for evaluating the performance of CLC on industrial scale was defined and simulated, and compared to other novel CO_2 capture technologies, power production with CLC-integrated steam cycle seems competitive. From these results we have a proposed CLC reactor concept which is flexible to use. Concept is based on circulation fluidized bed technology which is technically scalable to industrial size. This is relevance at technical and economical points of view at commercialize of CLC for CCS.

Future work in CCSP is more oriented towards calculations, modelling and techno-economic studies of the CLC process instead of experimental research. Main focus will be on techno-economical concept studies which are supported with modelling. In terms of modelling, the next step is to conduct a detailed scale-up study of gaseous fuel CLC using the developed models. After that, a selected solid fuel CLC concept will be added to the 1-D model, and the main objective is to construct a fully utilized and validated dual fluidized bed reactor system model for evaluating the performance of CLC reactors on industrial scale for both gaseous and solid fuels.

5. Transportation of CO_2

Although considered a commercially mature technology, CO_2 transportation issues are receiving more attention now as Europe aims to implement its first wave of CCS demonstrations. CO_2 transport networks will go through an intense risk assessment and permitting processes considering the environmental and public health issues, and finally the costs of CO_2 transport will have to be managed effectively as well. Ship transport of CO_2 is still without legal framework under the emission trading scheme, and although pipelines do have one, the European industry does not have experience on large pipelines operating in the high pressure required by CO_2 transportation. Assuming the technical and regulatory issues are solved, the form of the CO_2 transport infrastructure will have an impact on the price range of transportation from capture facilities around Europe, and likely an impact as well on where CCS can or will be implemented. According to the current knowledge, Finland is without any own geological formations suitable for long term CO_2 storage. Therefore, logistics and transportation of the captured CO_2 to foreign storage sites is a central element of all domestic CCS concepts.

Considering on-shore potential for storage of CO_2, suitable geology can be found within the north-eastern Benelux countries Belgium and Holland (GeoCapacity 2009a). The highest on-shore potential seems to be situated in North Germany, south-east from Hamburg and Lübeck. The potential on-shore storage areas closest to Finland are in western Latvia. Beyond EEA, great amount of on-shore storage potential are situated in East Ukraine and West Russia. The most potential off-shore storage areas are on the North Sea between Scotland and Norway and also near the east shores of England. In general, the North Sea and parts of the Norwegian Sea are abundant with potential storage sites. Some off-shore storage potential may also exist in the southern parts of the Baltic Sea (see also section 6).

The European Environment Agency (EEA) released an update to the CO_2 emission point sources containing E-PRTR data in November 2012. The now available database covers the industrial emissions for 2010. The emission release database covers facilities from food and beverage sector, chemical industry, energy industries and energy production, mineral industry, paper and wood processing, production and processing of metals and waste and waste water management. Emissions from the industrial sectors not included in the above are classified as other activities. The CO_2 emission release map over the Nordic countries has been updated in CCSP and is presented in Figure 18. Finland has numerous large point sources, which are mainly located in coastal areas.

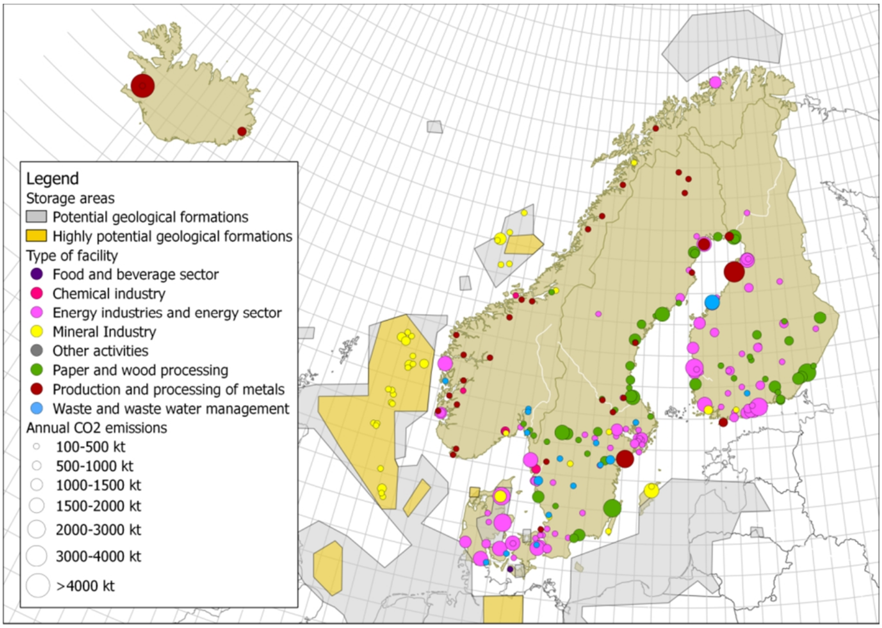


Figure 18. CO_2 emission sources (data from 2010) and potential geological formations for storage of CO_2 in the Nordic Countries. Map constructed by L. Kujanpää, VTT, using data from EEA & EU GeoCapacity.

Both pipelines and ships should be considered as possible CO_2 transport options for the Finnish power producers and the industry. Mainly coastal emission sources and long transport distances can favour ship transport over pipeline transport. However, pipelines would likely be used for collection of CO_2 into centralised export terminals to gain the benefits from the economy of scale. Large trunklines from capture plants to the geological storage areas could also be viable options from at least selected regions of Finland.

The research goal in CCSP on CO_2 transport has therefore so far been to generate scenarios and transportation cost estimates on future CCS infrastructure in North Europe, covering both transportation technologies. The evaluation of geological intermediate storage options has also been the focal point of research, as a part of ship transport infrastructure. The research has been conducted from a Finnish point-of-view, since corresponding studies typically view transportation on a global or EU-wide scale.

5.1 North European infrastructure for transporting CO_2 in 2050

A CO_2 transport cost estimation methodology has been created and used in assessing the transport costs in four North Europe-wide infrastructure scenarios for year 2050. For the cost estimation methodology, a set of transport cost equations were generated by fitting a surface to the lowest-cost results for a range of transport distances and annually transported CO_2 amounts. The infrastructure scenarios differed by the weighing between pipeline and ship transport modes and the selection between available storage areas.

The cost estimates generated results covering all the regions of North Europe. The scenarios clearly indicated that a shared CO_2 transport infrastructure is in general superior compared to independent transport projects by single CO_2 emitters. The transport cost of CO_2 from Finland to geological storage sites abroad includes a cost penalty compared to the coastal regions in countries around the North Sea. However, by joint transport infrastructure projects the industry and power production around the presented regions can reach significant cost reductions. The ship transport infrastructure benefits from a model where nearby capture plants are connected by pipelines to exporting terminal hubs. The transport cost for an in-land capture plant operator is quite sensitive to the pipeline distance, however. The smaller point sources far inland seem to have fairly high transport costs in the scenario calculations. The heavily industrialized regions on the shore of the Gulf of Finland can especially benefit from the shared infrastructure. Co-operation enables more economic transport of CO_2 for smaller capture facility operators. This results by default into heavier emission mitigation impact of the CCS implementation. As an example, a trunkline connecting all CO_2 point sources of over 0.5 Mt/a in the northern Bay of Bothnia to the Norwegian Sea seems to result in “competitive” costs for all involved parties and in significantly larger annually stored CO_2 volumes than in the case when only few larger plant operators would engage in CO_2 capture and ship transport.

The on-shore storage potential in western Latvia would provide a promising opportunity for CO_2 trunklines from other Baltics and from Finland. In the heavily CO_2 emitting regions of northern Germany, the local on-shore storage accessed by trunklines from the surrounding areas provide very competitive options for the local industry and power production.

Any mature CO_2 storage potential at the Southern Baltic Sea could enable considerable reductions of transportation cost by ships from Finland. However, as part of the CO_2 storage potential lies outside the European Economic Area (EEA) it could pose some additional challenges, as EU current legislation requires the storage capacity to be inside the EEA.

This study provides new grounds for assessing the position of Finland in the future of North European CO_2 transport infrastructure. Results map the competitiveness of CCS between the regions based on transportation costs, and give ideas on what kind of co-operation would result in a more cost-efficient infrastructure. The scenarios of CO_2 transportation networks are meant to have value both in the design for economic reasonability and in the selection of strategy for CO_2 transportation on corporate or public level.

In further work in CCSP the sensibility of generating a route optimisation model will be judged based on the results of the uncertainty analysis and at least on a qualitative evaluation of uncertainties in future changes related to emission sources and sequestration alternatives. If deemed meaningful, a route optimization algorithm will be developed and an optimized transport network from Finland will be produced still during the CCSP. In any case, the research will have an even stronger focus on CO_2 transport options for Finland.

5.2 Terminals and intermediate storage of CO_2

Exporting CO_2 from Finland by ships would require a terminal infrastructure, where the CO_2 is collected into intermediate storages from single or several capture facilities. Increasing the capacity of a terminal can lower the transportation cost due to a benefit from scale. Higher transport amounts of CO_2 would likely drive the unit sizes of ships and intermediate storage upwards.

Conventional intermediate storage units for CO_2 are formed by refrigerated cylindrical steel tanks. A volume of 3 000 m^3 per single tank has been proposed by Elsam, Kinder Morgan & Statoil (2003). Underground refrigerated caverns are a promising alternative technology for intermediate storage of CO_2. A cavern would require less above-ground surface area and can cause less costs than tank storage in the larger scale.

The goal of the work is to define and specify the characteristics of the geological intermediate storage option in comparison with other conventional intermediate storage methods above ground. Another goal is also to develop a methodology for geotechnical site selection and hydro-structural characterization of intermediate CO_2 rock cavern storages.

In this work, an intermediate underground storage case of a 50 000 m^3 unit has been investigated, including potential underground storage technologies. The investment cost of a storage unit has been estimated and compared to the investment cost of above-ground modular steel tank group of the same volume. The results underpin the commonly assumed economic benefits from investing into caverns instead of modular on-ground tanks for large, over 50 000 m^3 intermediate storages for CO_2. 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 the 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 in comparison 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 higher and lower estimates for both tank and cavern storages for CO_2 in the range of 50 000 to 120 000 m^3 are presented in Figure 19.

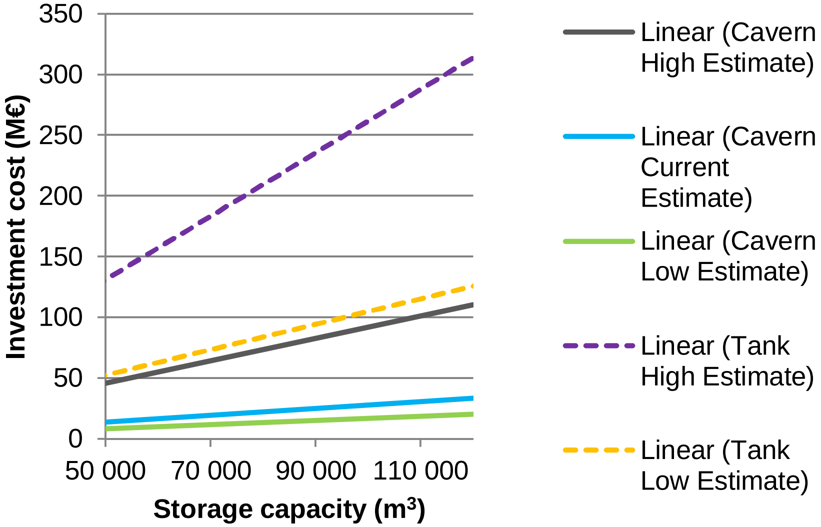


Figure 19. Comparison between investment cost of storage caverns and steel tanks, as found in literature. Based on Aspelund & Gundersen (2009), Svensson et al. (2004), Elsam, Kinder Morgan & Statoil (2003) and preliminary CCSP estimates.

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 0,224 M€/a to 0,557 M€/a (based on Aspelund & Gundersen 2009 and Svensson et al. 2004). Aspelund and Gundersen (2009) assumed an operation and maintenance costs amounting to 1% of the investment, resulting in this case from 0,0315 M€/a to 0,0785 M€/a. The operation and maintenance costs, represent therefore roughly 14% of the annual fixed costs of an above ground CO_2 intermediate storage when cost related to liquefaction process are neglected. When the reliquefaction cost resulting from the operation of a single 3 000 m^3 tank unit are taken into account and the operation and maintenance cost are neglected, the annual cost of the unit amounts to 0,231 M€/a to 0,564 M€/a. The reliquefaction costs, equalling 0,007 M€/a per a 3 000 m^3 tank, represent roughly 1–3% of the annual cost. 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 cost without operation and maintenance costs.

As one of the obvious CO_2 emission hot-spots, the Kilpilahti oil industry area has been investigated as a potential environment for CO_2 intermediate underground storage. Furthermore, abandoned mines have been checked as potential intermediate CO_2-storages, but in most cases they are not suitable for the purpose.

6. Storage and utilisation of CO_2

CCS is a chain of operations, which all have to be organised in a reliable, sustainable and feasible way. Perhaps the most essential and critical part of the CCS chain is the final storage of CO_2. The volumes to be stored are extremely large, which significantly reduces the number of potential solutions. Only a few credible storage methods have been presented, mostly based on geological storages. The applicability of other alternatives is mainly restricted by capacity and/or economy. However, alternative methods are under development in order to improve their competitiveness. Also, certain options for utilisation of CO_2 could contribute significantly to CO_2 emission reduction locally.

Geological storage of CO_2 is the only storage method, which has been demonstrated in industrial scale and is currently seen as the most potential storage option. From Finnish point of view this means transportation of CO_2 abroad because no potential storage sites have been identified inside the borders of Finland. The nearest identified and demonstrated geological storage sites are located on the North Sea. The Baltic Sea region has some theoretical potential that up to now has not been studied in detail. As the distance from Finnish emissions sources is much closer to the Baltic Sea than to the North Sea it provides an interesting opportunity for geological storage. Thus, international R&D activity has been established as part of CCSP for focusing on this option.

Beside geological storage, other storage technologies have also been developed. In Finnish conditions fixation of CO_2 to mineral matter might offer an alternative for CO_2 storage in specific cases. This topic has been studied in Finland already several years in laboratory scale and results have encouraged continuing development work towards piloting and demonstration. A lot of expertise and industrial activity in the field of geology and large-scale mineral and ore processing is already available in Finland. Besides the earlier identified large potential for central and northern Finland, interesting opportunities for south-west Finland are offered by magnesium silicate mineral resources at Vammala and Suomusjärvi. The development work is further supported by international project cooperation, as Finland’s expertise in the field attracts interest from abroad. An aspect that drives the interest of international R&D consortia is the option to apply mineralization directly to CO_2-containing gases, avoiding a costly and problematic CO_2 separation step.

In addition to permanent storage of CO_2 some industrial applications of CO_2 could offer potential to utilise CO_2 as a raw material and this is gaining interest among industry. Examples of industrial utilisation could be the use of CO_2 as a raw material in chemicals and fuels production, for production of inorganic carbonates from ashes and slags, as a solvent or in enhanced cultivation of algae. Sustainability assessment analyses and life cycle analyses are needed in order to evaluate real potential and sustainability of these CO_2 utilisation alternatives in connection to CCS besides the estimation of economic boundary conditions.

6.1 CO_2 storage assessment at Baltic Sea area

From Finnish and Baltic Sea region point of view, perhaps the most well-known and significant sites suitable for geological storage of CO_2 are located in the North Sea, which is relatively far away from Finland. However, the Baltic Sea region might also have potential storage sites, but these have not yet been studied systematically.

In the CCSP R&D program, the Bastor-project, is assessing the CO_2 storage potential of the Baltic Sea. Several countries have borders on the Baltic Sea and therefore the Bastor-project is implemented in tight international collaboration. The overall objective of the Bastor-project is to evaluate the CO_2 storage potential in Baltic Sea region. The main focus is on off-shore storage. In practice, the study is being implemented by an Irish expert organisation, SLR, who has specialised on evaluation of geological storage capacities. In addition to SLR, an Australian expert organisation, CO2CRC, is used for the implementation of the work.

In CCSP, the first part of the Bastor-project has assessed the potential for geological storage of carbon dioxide in sedimentary basins in the bedrock of the Baltic Sea region (Vernon et al. 2013). A compilation of available digital data from well logs, seismic line data interpretations, mapped structure outlines and published material from existing hydrocarbon fields and identified and mapped structures from Sweden, Poland, Latvia, Lithuania and Kaliningrad have been incorporated into a GIS database for the Baltic Sea region. A detailed screening of regional sedimentary basins identified the Slupsk Border Zone as having suitable structures for storage of CO_2 in depleted oil and gas fields or saline aquifers.

Cambrian sandstone saline aquifers below 900 m have been identified as the principal regional potential storage target with the Dalders Monocline as the most promising area. Eight individual structures were identified as having greatest potential. Detailed 3D geological static models were developed for three of these structures located in offshore Latvia and one cross-border structure – the Dalders Structure (Figure 20).

A theoretical regional CO_2 storage capacity calculation based on the GeoCapacity (2009b) methodology was undertaken. A regional storage capacity for Cambrian sandstones below 900 m was estimated at a total of 16 Gt, with 2 Gt for the Dalders Monocline (Figure 20). Theoretical storage estimates for individual structures for the Baltic Sea regions includes 760 Mt for the Latvian structures and the Dalders Structure, 9.1 Mt for the structures located in Poland, 31 Mt in Lithuania and 170 Mt in Kaliningrad. These estimates are based on the best available data at the time of writing. However, these estimates will be improved upon as new data becomes available from other sources.

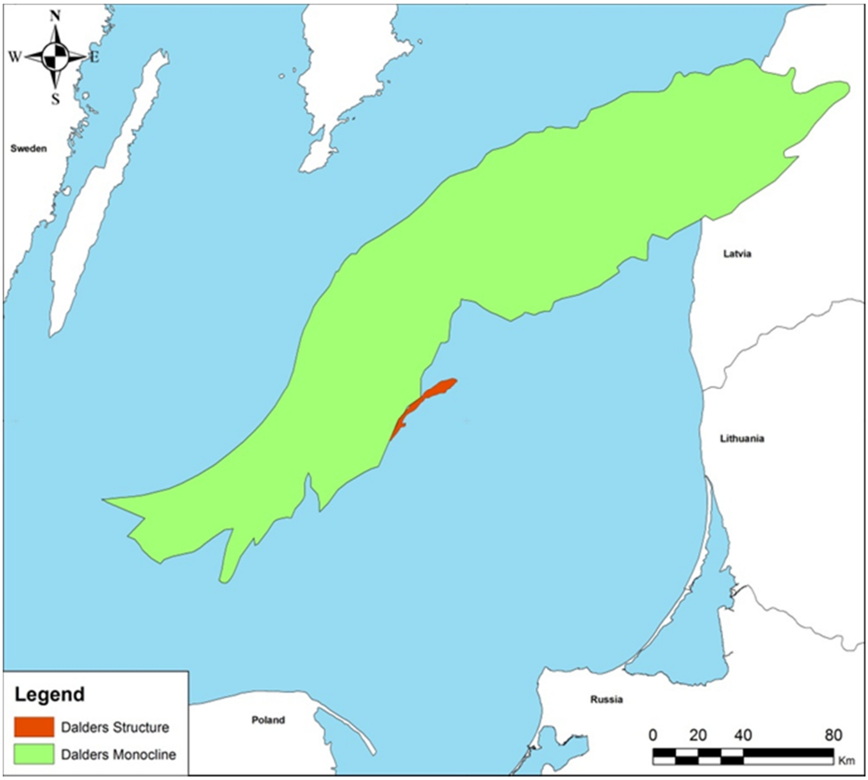


Figure 20. Location of the Dalders Prospect Structure and the Dalders Monocline (Vernon et al. 2013).

During the second part of the Bastor-project more data from different areas of Baltic Sea will be gathered and more detailed modelling will be done in order to evaluate the practical storage potential. This work will be completed in collaboration with the Swedish CCS project.

6.2 Fixation of CO_2 by producing PCC from steelmaking slags

Fixation of CO_2 to mineral matter offers an alternative for geological CO_2 storage. This topic has been studied in Finland for more than a decade on laboratory scale and results have encouraged continuing development work towards piloting and demonstration.

The Slag2PCC process route, developed in Finland, aims at converting calcium containing industrial by-products (with main focus on steel converter slag) into valuable precipitated calcium carbonate (PCC) product (Said et al. 2013). In this method, an aqueous solution of ammonium salt is used to selectively extract calcium from the by-product/waste material (Figure 21). After removal of the solid residue, CO_2 is bubbled through the solution producing stable calcium carbonate as an end product. Ammonium salt solution is recovered simultaneously and can thus be reused. In order to sequester 1 t of CO_2 by using this concept, approximately 5 t of steel converter slag would be consumed, and 2 t $CaCO_3$ end product, as well as 3 t of residual slag, would be produced. If the produced $CaCO_3$ is used to replace conventionally manufactured PCC then additional CO_2 emissions reductions are gained as the conventional PCC production method is very energy intensive.

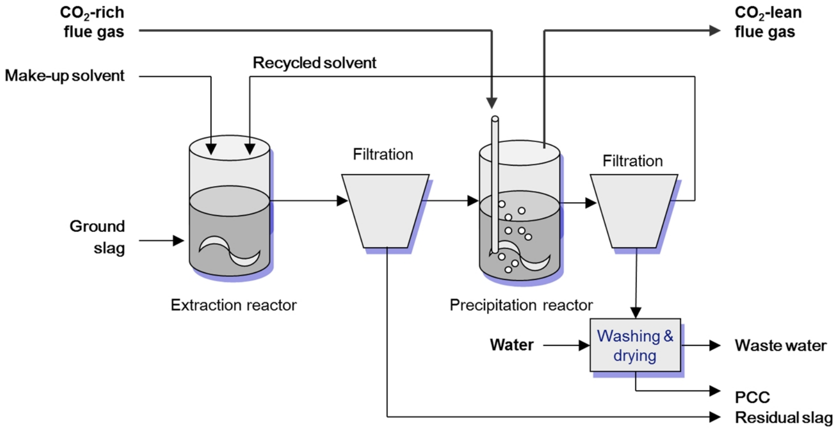


Figure 21. The Slag2PCC process: calcium is selectively extracted from steelmaking slag and reacts with CO_2 from flue gases to produce precipitated calcium carbonate.

The process benefits from the fact that it proceeds at room temperature and pressure, its end product is likely to have significant market value, and it does not consume significant amounts of chemicals. In addition, it uses raw material that is readily available, has a low price and requires some treatment and handling anyway. Furthermore, it is likely that flue gases could directly be used as a source of CO_2, which would avoid the need for a costly and problematic CO_2 separation step.

The Slag2PCC concept was first developed during the Tekes – the Finnish Funding Agency for Technology and Innovation funded projects Slag2PCC and Slag2PCC-Plus (2005–2009), while current development work is mainly funded by the CCSP program. Since the start of the program, the concept has been taken from a two-stage batch process towards a continuously operating process that produces quite a good quality PCC and the design parameters for larger scale have been determined. A design for a pilot-scale test facility (three reactors á 0.25 m^3) has been completed and it is being built at Aalto University (Figure 22) while a smaller lab-scale process unit at Åbo Akademi (reactor volumes ~25 litres) has been built and taken into use for supporting the optimization work. The objective of the current development work is to move the concept further towards commercial application, aiming at processing 25 t/h steel converter slag into 10t/h PCC.

One of the main challenges of the concept is the quality of the end product PCC. While purity of the end product satisfies the criteria for industrial use PCC (≥ 97% $CaCO_3$), particle sizes produced so far are too big (commercial size would require the main part to be < 5 µm) and particle shape and crystal form are not yet fully controllable. The quality of the process residue (spent steel converter slag) is also problematic. It would be easier to find new utilization options for the spent slag, if leaching of the harmful elements could be reduced. Various process steps (such as solid/liquid separations) also present a challenge to concept development. Therefore, current research focuses on solving these issues.

Figure 22. Pilot facility under construction at Aalto University.

6.3 Magnesium silicate rock carbonation

Driven by a range of well-documented motivations (such as large mineral resources in many locations like Finland, production of useful materials, no need for CO_2 storage monitoring, etc.) CO_2 mineral sequestration is being developed in the CCSP program. This is further supported by the ongoing international R&D efforts to find cost-effective use of CO_2 or other products related to the CCS chain, which can assist in covering the costs for CCS.

More than a decade of work that originally started at Aalto University has been further developed in Åbo Akademi to what has become known as “the ÅA route” for stepwise carbonation of serpentinite, a rock composed mainly of magnesium silicate mineral serpentine. Similar to other research groups the chemical reaction kinetics of the process steps have received much attention but the work done in CCSP is unique in having the minimization of energy input and chemicals use as starting points as well. Energy is recovered (as ~500ºC heat) from the carbonation reaction (Fagerlund et al. 2012). Current trends – certainly in part due to Åbo

Akademi's work – show several routes that focus on the use of ammonium salts and integration with CO_2 removal from (flue) gases. These salts are relatively cheap and in principle fully recoverable within the process routes that make use of the fact that the sulphate of magnesium, extracted from rock, is water-soluble. Another trend is to apply mineralization on the CO_2-containing gas directly, without the expensive (and for oxygen-containing gases challenging) capture step of a CCS process train.

The "ÅA route", as depicted in Figure 23, comprises extraction of magnesium from rock using ammonium sulphate salt in a 400–450ºC solid/solid reaction followed by precipitation of magnesium hydroxide (besides iron hydroxide) in aqueous solutions, using ammonia vapour from the upstream solid/solid reaction for raising pH levels. Subsequently, the magnesium hydroxide is carbonated within ~10–30 minutes in a pressurized fluidized bed reactor at ~500ºC, 20 bar CO_2 pressure, producing ~1/3 of the heat needed for the magnesium extraction (Fagerlund 2012, Nduagu 2012, Romão et al. 2012). Conversion levels obtained so far are 80% and 70%, respectively, for the production and carbonation of $Mg(OH)_2$ produced from serpentinite.

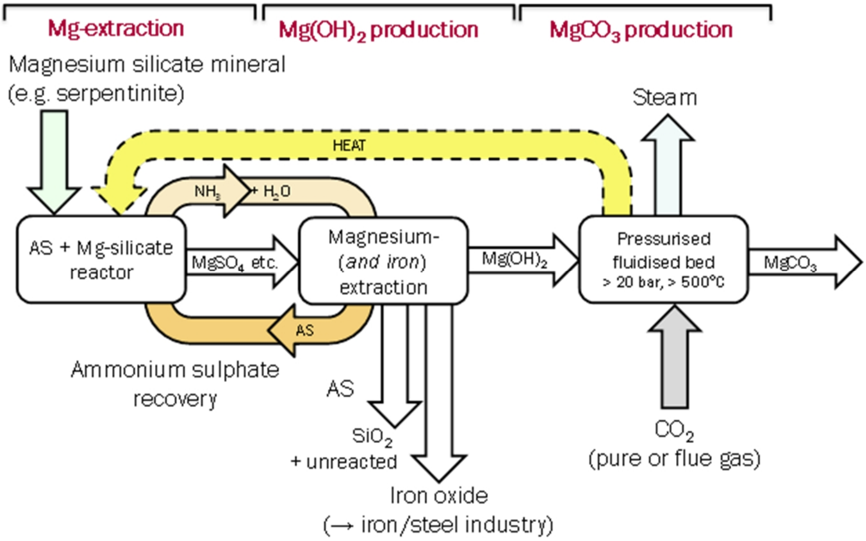


Figure 23. The mineral carbonation process concept ("ÅA route") developed by Åbo Akademi.

Application of the mineral carbonation process at an industrial lime kiln is under consideration in CCSP: a recent study shows that operating at 80 bar carbonation pressure with ~22%€/-vol CO_2 flue gas without capture, mineral sequestration may be accomplished at an energy penalty of 0.9 GJ/t CO_2 electricity besides 2.6 GJ/tCO_2 heat which can be extracted from the kiln gas (Slotte et al. 2013). Another application that has been considered is the mineralization of CO_2 from the Meri-

Pori power plant using rock at Vammala, ~85 kg east of the power plant (Zevenhoven et al. 2012).

For application outside Finland Åbo Akademi is cooperating with partners in Singapore (with Tekes co-funding), aiming at large-scale application of CCUS (carbon capture, utilisation and storage) for land reclamation by around year 2020, and in Portugal, where very large resources of mineral are available in the north-east of the country, at a stone-throw from the large-scale oxy-fuel power plant demonstration at Ciuden, Spain.

6.4 CO_2 utilisation

Carbon dioxide is already used in commercial processes, both in its pure form and as a feedstock in the synthesis of bulk chemicals and fuels. In the pure form CO_2 is presently used in many industrial sectors for several purposes (Figure 24). For example, it is used to carbonate drinks in food industry or to accelerate production in greenhouses. As an inert and safe gas it is also used as a protective gas (in chemical or steel industries, in food preservation, in welding etc.) and as a fire extinguisher. Likewise, large quantities are also used as solvents in processes such as dry cleaning and decaffeination. Carbon dioxide is also used in enhanced oil and gas recovery by pumping it under near critical or supercritical conditions into oil fields where conventional recovery has become uneconomical or impractical.

As an economic, safe, and renewable carbon source, CO_2 turns out to be a tempting carbon-based building block for making chemicals and materials. The utilization of CO_2 as a feedstock for producing chemicals not only contributes to mitigating global climate change caused by the increasing CO_2 emissions, but also provides a grand challenge in exploring new concepts and opportunities for catalytic and industrial development. As a matter of fact, the utilization of CO_2 is the only technology that may produce profit out of the recovered CO_2, while contributing to reducing its global emissions.

Several industrial processes use CO_2 as a feedstock, and R&D is being undertaken to increase such applications. The current industrial use of CO_2 is about 130 Mt/a worldwide, of which the production of urea is the largest consumer of CO_2, accounting for 60% of the total amount (Aresta & Dibenedetto 2007). Other uses include the production of intermediate chemicals required by the chemical industry, such as carbamates, carboxylic acids, inorganic complexes and polymers (Figure 25).

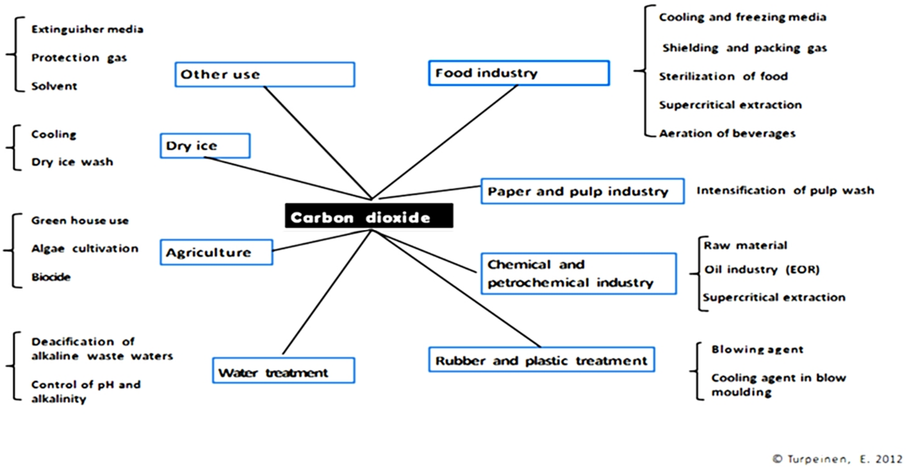


Figure 24. Sectors where CO_2 is utilized.

However, in most cases CO_2 is eventually released back to the atmosphere at the end of the life-cycle of the product, which can range from days to decades (and in some cases centuries). Recent estimates of the maximum use of CO_2 as a feedstock for chemical products are 180-230 Mt/a worldwide (VCI & DECHEMA 2009, Styring et al. 2011), which is a small potential contribution in relation to global anthropogenic CO_2 emissions (around 32 Gt in 2012). However, despite the fact that, currently, the usage of CO_2 in the chemical industry cannot reduce significantly the global CO_2 levels, it is believed that the full potential of the fixation of CO_2 into value added products has not yet been completely explored. The further development of industrial processes that are utilizing CO_2 for high-demand products is of importance.

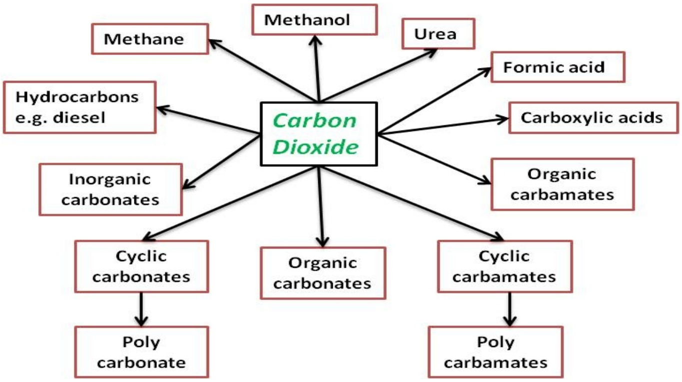


Figure 25. An overview of chemicals production from CO_2.

CO_2 can also be used as a feedstock for the production of fuels such as methanol and synthetic liquid hydrocarbons. For example, VCI and DECHEMA (2009) estimate that a maximum of 2 Gt/a CO_2 could be used for fuel synthesis. Although the amount of energy required to produce liquid synthetic fuels exceeds the recoverable energy, they allow storage of energy and can easily be used in transport applications. Their production may be supported by renewable energy sources as a way of balancing supply and demand in the future electricity systems dominated by variable renewable energy sources.

In CCSP, various technologies and concepts in which CO_2 can be utilized by industry have been screened and the most promising ones are being evaluated. Also, attention is given to the sustainability (economic, environmental and social aspects) of the technologies and concepts and their greenhouse gas mitigation effects.

Three processes were found promising in terms of viable future CO_2 utilisation routes: production of synthesis gas, methanol and dimethyl carbonate. A preliminary sustainability assessment and comparison against conventional production routes was performed for these (Kinnula 2013): syngas production via steam methane reforming (SMR) vs. dry reforming (CO_2 reforming), syngas based methanol synthesis vs. methanol synthesis using CO_2 and dimethylcarbonate (DMC) production via oxidative carbonylation vs. direct synthesis of DMC via CO_2. Dry reforming was found to be environmentally a more sound process than SMR but it had a lower economic competence. Methanol synthesis via syngas showed slightly better overall sustainability than the CO_2 based reaction. DMC production via oxidative carbonylation was more cost-effective than the CO_2 route but the CO_2 based route was environmentally and socially more sustainable.

Similar comparison was done for processes producing formic acid, comparing routes using CO_2 with conventional formic acid production routes. The results from the assessment showed that the conventional route was harmful to the environment while the CO_2 utilization routes were beneficial to the environment (Omodara 2013). The CO_2 utilization route was economically more viable than the conventional, but more development work is needed on the CO_2 utilization route to fulfil its potential.

In future work in CCSP the sustainability assessment analysis methodology will be further developed based on the experience gained from the previous cases and it will be applied to new CO_2 utilising reaction routes. Preliminary laboratory tests for methanol synthesis will be performed. Moreover, utilization of CO_2 as a solvent will be evaluated in both catalytic dimerization and trimerization reactions. The viability of the most potential CO_2 utilizing reaction routes will be elaborated and assessed experimentally. All the CO_2 chemical utilising routes will be summarized in one report to get the overall understanding of the potential of industrial utilization of CO_2.

6.5 Algae cultivation

Enhancing the growth of microscopic algae (microalgae) with CO_2 from a flue gas source has been considered a promising approach both in terms of CO_2 capture and utilisation and in renewable energy production. Being simple organisms, algae grow quickly when sufficiently CO_2, water, and nutrients are available, and therefore produce abundantly biomass which in addition has a high energy content due to the high amount of lipids. Hence, integration of algae cultivation with a CHP plant providing CO_2 and heat, and a municipal waste water source providing water and nutrients, has been suggested a concept that combines carbon capture, biofuel production, and waste water treatment.

In CCSP, the potential of algae for carbon capture and utilisation was experimentally assessed from the point of view of their tolerance towards potentially toxic substances in unpurified CHP flue gas, such as nitrogen and sulphur oxides. It was concluded, that the tolerance is dependent on the algal species, and there were indications that certain species could even utilize the nitrogen and sulphur in the flue gas as nutrients. Currently, conditions are being identified, in which algal CCS and biofuel production could be feasible from the point of view of energy balance and environmental sustainability, and the most critical phases in microalgae cultivation process in terms of energy consumption and sustainability are being identified.

In CCSP, algae cultivation for carbon capture and utilisation is also being assessed on a concept level. The main purpose in the modelled, hypothetical cultivation plant is to utilize the CO_2 from a nearby district heating power plant, and nutrients from a nearby waste water treatment plant. Based on the reviewed research studies, two different algae cultivation systems were selected for the analysis: open pond, and tube photobioreactor (PBR). The system boundaries of the studied system are presented in (Figure 26). At this point, system boundaries were set to include biomass processing until the harvesting and dewatering step, i.e. the final product was not specified.

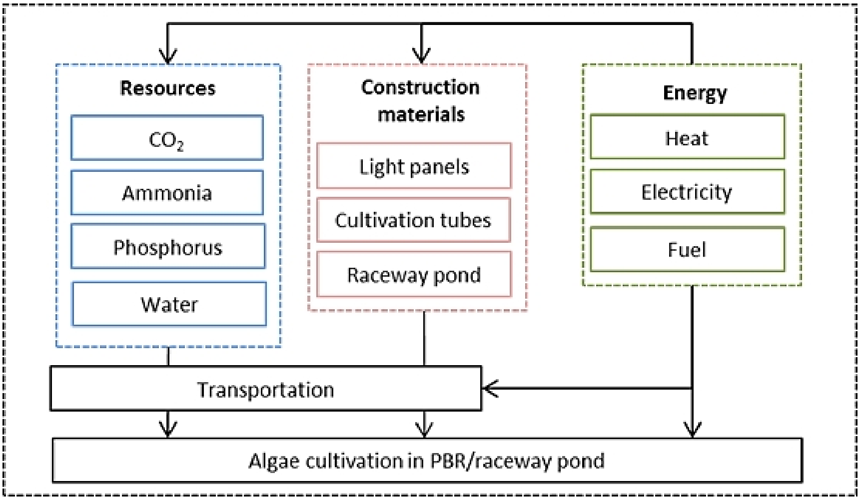


Figure 26. System boundaries in LCA analysis.

The main bottlenecks for developing this concept sustainably were identified with the life cycle analysis (LCA) tool SimaPro, by utilizing data from the existing research literature. The system was assessed from the point of view of three elements: energy consumption, other resource requirements (e.g. CO_2, nutrients, water), and construction material requirements.

The environmental effects were assessed with the aid of several impact categories, among which freshwater eutrophication, terrestrial acidification, and climate change were identified as the most critical. Energy consumption was identified as the most critical element, from two perspectives. Firstly, energy consumption frequently appeared as the major factor in the environmental effects. For this reason, e.g. the selection electricity profile for modelling (e.g. hydro vs. coal) had a significant impact on the overall sustainability. Secondly, assumptions related to the amount of energy required in different process steps need further research – especially related to the provision of light, circulation of water into and within the system, as well harvesting and dewatering of biomass. In the latter, especially the possibility of utilizing of waste heat from the CHP plant requires further attention.

On the other hand it was concluded, that the availability of land area for the cultivation has a profound impact on the CCS and nutrient removal potential of the system. From dozens to hundreds of hectares of cultivation surface may be required for any considerable portion of CO_2 or nutrients to be fixed. Tubular photobioreactors allow more cultivation surface with smaller land area, but this is partially limited by the energy consumption required for extra lighting for dense cultivations.

During CCSP these identified bottlenecks will be assessed by more thorough research on energy balances and process design optimization, in order to reduce energy consumption and increase biomass production. Additionally, the system boundaries will be enhanced so that the optimal end product pathways can be identified. This will include assessment of yields, energy balances, and sustainability related to the production, conversion and utilization of different end product alternatives.

7. Regulation, legislation and EHS

CCS is still a young, complex technology infrastructure and thus environmental as well as safety issues have not yet been developed nor understood in detail. Many parts of the CCS process are well known and can be considered state-of-the-art but the deployment of complete CCS chains (covering from capture to storage) is so far limited to a handful of demonstration-scale units.

Legal frameworks concerning CCS have been evolving during the past years. They include international treaties, EU regulations and directives and national laws and decrees. One of the objectives in CCSP has been to keep track of the evolving regulations affecting the implementation of CCS in Finland. Moreover, the goal has been to support the development of the needed regulatory framework by finding its current weaknesses and underlining future work to create a suitable environment for CCS in Finland. The legislative framework for CO_2 transportation is in special focus since it is crucial for a country without known possibilities for geological storage of CO_2.

Also environment, health and safety (EHS) issues of industrial activities and transportation are controlled by international and national regulations and requirements. Prevention of accidents and environmental damages, as well as ensuring safety and well-being of people are among the key objectives of the responsible companies all over the world. The establishments introducing CCS technologies are no exception of the EHS requirements. Therefore, an overview of the EHS-requirements relevant for the various life-cycle phases of establishments introducing CCS technologies and CO_2 transportation has been made in CCSP.

Considerable amount of regulatory data has been collected and assessed during the work, resulting in annual regulatory status reports and two guidebooks on EHS issues on capture and transportation parts of CCS. Additionally, a report on the monitoring of transported CO_2 by ships has been made. The latter discusses the gap between the current monitoring and reporting regulation under the EU's Emissions Trading System (EU ETS) and possible future ship based transportation of CO_2 for the purposes of CCS. The results include an outline of monitoring procedure for ship transportation.

The results are meant to serve the decision makers as a source of concise information on legal issues concerning CCS, including any regulations still in the preparation. For owners of power plants, industrial plants or for future owners of

CO_2 pipelines and intermediate storage facilities it is important to be aware of the upcoming changes in European and Finnish EHS legislation and requirements possibly affecting the CCS process.

7.1 Legal and regulatory framework for CCS

In the latest regulatory status report, the existing and emerging regulatory framework was tested through comparison to a published model framework (IEA, 2010) to obtain a general qualitative view on the effectiveness and maturity of the legislation concerning CCS implementation. Additionally, possible EU's legal frameworks in preparatory stage were identified.

The legal framework enabling the capture, pipeline transport and geological storage of CO_2 is nearly settled into place across the EU member states. Finland has adopted the amendments into existing national legislation required by the CCS Directive (EC 2009) and transposed the remaining requirements of the directive into a new act in July 15th 2012 (FINLEX 2012). Further possible amendments in preparation to existing legislation or new legal frameworks have not been identified.

The national legal framework on CCS seems to address most of the key issues identified in the IEA model regulatory framework (IEA 2010) on capture and storage of CO_2. Concerning storage of CO_2, a comparison is not meaningful, as geological storage was prohibited in Finland. The comparison between the enacted legal framework to the key issues or requirements identified and reposted by IEA (2010) pointed out open question mainly on the field of transport of CO_2 and inclusion of the capture of CO_2 from biogenic sources.

Concerning the pipeline network access, how well a third or n:th party access can be ensured in practice is a question of the designed flexibility of the future transport network and the dispute settling ability of the Energy Market Authority. Inclusion of ship transport of CO_2 as a valid CCS mechanism under the EU-ETS would likely require addressing and amending the transport network access article of the CCS Directive and the resulting national legislations. Aside from the CCS Directive and the resulting national legislations, an amendment to the monitoring and reporting regulation under the EU-ETS will have to be made to enable ship transportation of CO_2 for the purpose of geological storage.

Ship transport of CO_2 is at the moment hindered also due to the London Convention. As the amendments allowing the export of CO_2 under the London Convention remain waiting for ratifications, off-shore storage of CO_2 captured from Finland would still be prohibited. Finland can take an active role with neighbouring regulators to come up with a tailored solution to the issue.

In addition to ship transport of CO_2, capture of CO_2 from biogenic sources is a relevant issue when considering a large-scale implementation of CCS in Finland. Inclusion of Bio-CCS into the emission trading mechanism will hardly happen in the short-term, as this would require more political pressure or interest from the industries. After all, implementation of CCS value chains in Europe has yet to get going as the first call of NER300 funding resulted in withdrawals of all CCS project applications.

The new EU legislation on CCS and ETS, and also the international treaties on the protection of marine environment have a high level of importance regarding the future of CCS in Finland. The most obvious question marks regarding the evolving legislation are the inclusion of ship transportation to the monitoring and reporting regulation of the EU-ETS and the ratifications of the article of the London Convention that would enable cross-border transport of CO_2. The new emission monitoring and reporting regulation under EU-ETS is unfavourable for Finland as the emissions avoided through CCS based on ship transportation of CO_2, BioCCS, or activities such as manufacturing of precipitated calcium carbonate or mineral carbonation will not be accounted for. Evolution of EU legislation on CCS and ETS will have to be actively observed and interacted with in order to build regulatory grounds for economically viable Finnish CCS operations in the future. This regulatory follow-up has been planned to continue in CCSP, including annual updates on the regulatory status report and the EHS guidebooks.

7.2 CCS from an EHS perspective

The implementation of various technological options for carbon capture and transport can due to environmental, safety and health (EHS) issues be a lengthy procedure, which has to be started several years before the installation is taken into use. Also after commissioning, the lifespan of the installation is likely to include several points, where the EHS issues have to be revisited, related documents updated, and training courses and dissemination schemes repeated.

In CCSP, two guidebooks have been made that review the current legal EHS requirements for carbon capture and transfer in Finland. The first guidebook (internal deliverable number D112) concerns the EHS-requirements for ships and seafaring (carrying CO_2) within Finnish territorial waters. The second guidebook (internal deliverable D102) cover the requirements related to the capture, transfer and intermediate storage of carbon dioxide. These guidebooks form the basis for future environmental, health and safety (EHS) assessments in CCSP.

The first guidebook (D112) contains description of the current national and international requirements of EHS issues in terminal operations and marine transportation. It also includes descriptions of temporary storage, loading process, and ship transportation of carbon dioxide. In addition to that the most potential hazards of CO_2 in terminal loading and marine transportation are considered. Marine transportation of carbon dioxide is relatively safe compared to the other hazardous substances transported at sea, and the most potential risks are already well-known. However, the cooling substances as well as the cooling and capturing processes of CO_2 during loading and transporting are issues which require special attention.

The guidebook on EHS requirements related to the capture, transfer and intermediate storage of CO_2 in Finland (D102) covers the EHS issues relevant for the various life-cycle phases of establishments introducing some of the best documented CCS technologies like post-combustion, pre-combustion and oxy-fuel combustion. EHS issues of CO_2 pipeline transportation from a power plant or an industrial source to a Finnish harbour and intermediate storage of CO_2 in the harbour are also considered. In addition to carbon dioxide, there are several other chemicals involved in the various carbon capture technologies. The data package covers EHS issues related to the handling and storage of six common chemicals present in the various CCS reference technologies. These chemicals are carbon dioxide, carbon monoxide, hydrogen, monoethanolamine, oxygen, SelexolTM solvent. In addition to these chemicals, EHS issues related to solid oxygen carriers used in chemical-looping-combustion technology are also described.

The focus of the work has been on what current legal environmental, health, and safety requirements an operating company must fulfil, when introducing various technologies for carbon capture in Finland. Although CO_2 is generally not classified as a hazardous substance, various sections in the Finnish legislation will apply when carbon capture technologies are introduced at power plants and other industrial establishments in Finland. Emphasis is put on those obligations, which, when carbon capture technologies are employed, will be different from those of conventional installations.

The study comprises the following three types of onshore facilities: industrial facilities (including power plants) in which CO_2 is formed, pipelines for carbon dioxide transfer to Finnish harbours, harbour facilities including intermediate storage tank(s) and ship loading facilities. As capture, transfer and intermediate storage of carbon dioxide can be carried out in many different ways, there has been a need to restrict the discussion to a limited amount of technology options. Representative cases for post-combustion and pre-combustion carbon capture are used as reference. Also an oxy-fuel case study is presented. In addition, a pipeline case and an intermediate storage and harbour facility are used as examples.

Each topic starts with a General Requirements section. In this section the basis of a law is explained as are those requirements in the legislation that concerns carbon dioxide sources (power plants and other industrial installations), transfer lines as well as intermediate storage facilities. The General Requirements section is followed by Case Specific Requirements sections, in which additional specific requirements concerning each of the various types of installations are described.

As one of the outcomes, a road map presenting the milestones of CCS project from an environmental and legal perspective has been created (Figure 27). It includes the EHS requirements and licensing procedures for capture, transfer and intermediate storage of CO_2. The road map is presented as a web based demonstration tool in which the main topics are further discussed via hyperlinks. The road map is made easy to use in which the user finds the needed information of a particular step with the least effort. The road map gives also the overview of the whole regulatory process for implementing a CCS project.

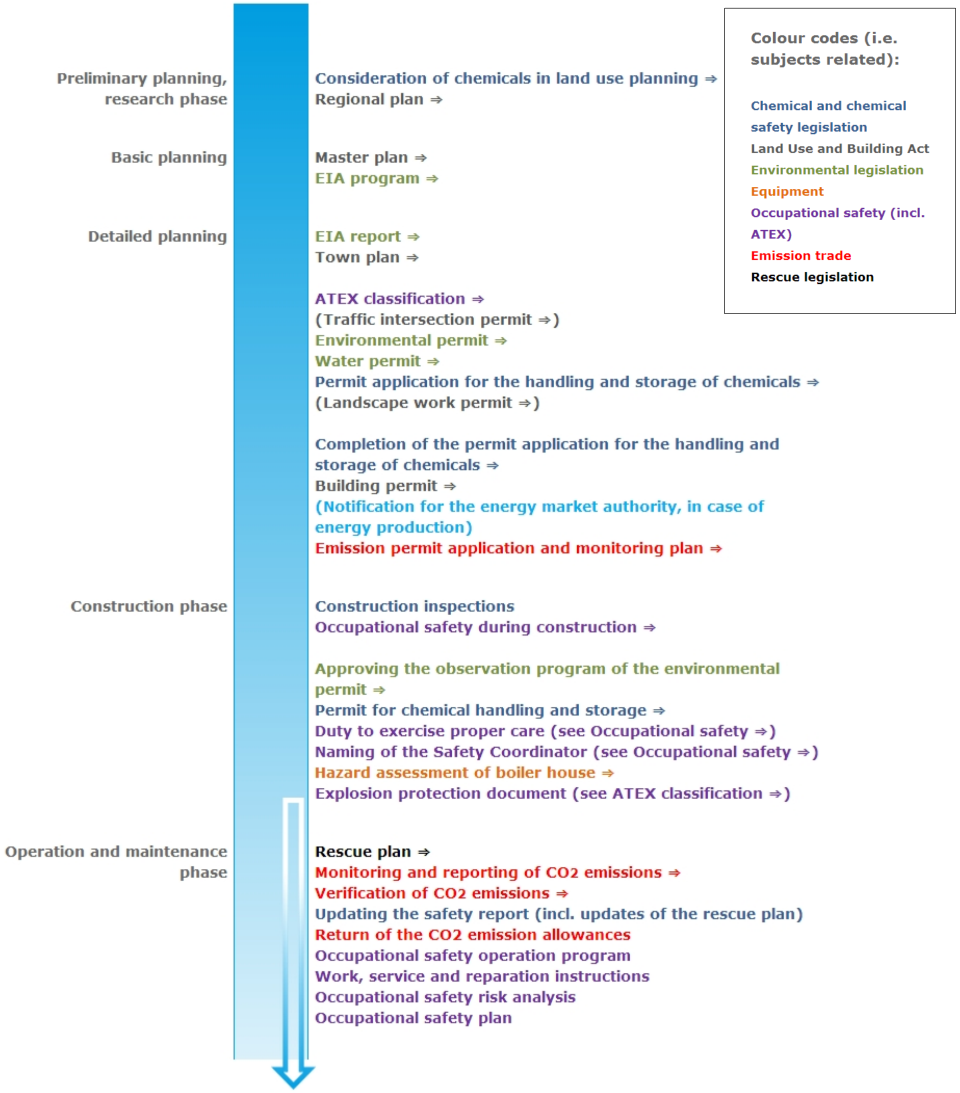


Figure 27. CCS project timeline, as presented in the web-based road map tool.

Several steps are included, which need to be considered when initiating a CCS project in order to find out the social and environmental impacts. The significance of each step has been evaluated and the possible risk stages for the project have been identified. Figure 27 gives an overview of the main EHS steps during the entire life cycle of installations designed to enable carbon capture and transfer within Finland. Along the CCS project timeline, the relevant legislation and general description is given on each of the phases and milestones. Additionally, time estimate needed for the stage is given and responsibilities and the decision maker are identified. Other addressed issues are:

- Impacts of CCS on the current protocol
- Hearing/Interaction requirements
- Appeal procedures
- Connection to other stages
- Expenses.

8. Acceptability of CCS

Research on public acceptance of CCS is intensifying but studies covering the Nordic Countries still remain scarce. Public acceptance can be one of the major bottlenecks that may seriously hinder timely application of CCS. Education and engagement of the public and sufficient communication are necessary steps to improve public awareness of the topic. Therefore, public acceptance is an important topic covered in CCSP.

Public acceptance and acceptability have recently been actively discussed in relation to different controversial technologies. One reason for being in the focus of attention is seen to be the lack of progress in the commercialization of technologies. The negative consequences have served to emphasize the importance of public acceptance in the strategic development, application and commercialization of technologies. Lack of progress and public opposition can also be seen as a result of approaches applied in planning and implementation. Participatory approaches and understanding of technologies as socio-technical combinations have emphasized the role of stakeholder engagement in planning and decision-making.

Stakeholders can play a double role in the development of CCS technology, i.e. (1) a direct influence on the implementation of CCS projects and presumably also much better chances to influence policymaking compared to lay people and (2) indirect influence on the deployment of CCS because of their ability to shape the public opinion. This raises the question how the Finnish stakeholders perceive CCS. Do they accept CCS technology?

Debate in the mass media influences public perception of new technologies such as CCS technology. A recent survey (EC 2011) indicated that CCS is fairly unknown technology in Finland. The low awareness calls for analysing to what extend CCS technology has been discussed in the Finnish media. Media studies have been conducted at the national level for example in Australia, the Netherlands and in Sweden, but not so far in Finland.

The first part of the study made in CCSP was based on interviews with twelve Finnish stakeholders representing industry, the authorities, non-governmental organisations and a research organization (Kojo & Nurmi 2012). The interviewees were selected based on (1) stakeholders' statements on the national implementation of the CCS Directive (EC, 2009) collected by the Ministry of the Environment in 2011, (2) researcher's own consideration and (3) interview feedback. Furthermore interview feedback, i.e. a snow-ball method, was applied to make sure that all potential stakeholders were identified.

The second part of the study made in CCSP was based on print data set comprised of 226 articles providing a comprehensive view over the CCS debate in the Finnish print media (results not yet published, internal deliverable D123). The study covered the time period from the 1st of January 1996 to the 31st of August 2012 (Figure 28). Data covered ten Finnish-language newspapers. They were retrieved from two newspaper databases: Media-arkisto and Sanomat-arkisto.

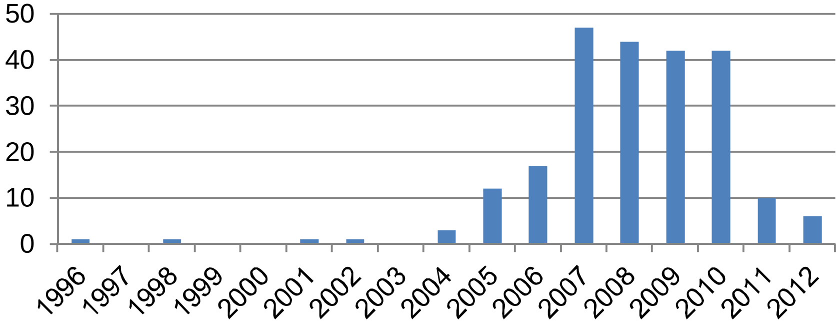


Figure 28. The number of articles with a reference to CCS published in the chosen Finnish daily newspapers in the period 1996–2012.

8.1 Stakeholders’ opinions to CCS

The results from the interviews showed that CCS technology is currently not a burning issue in Finland. The stakeholders interviewed stated that they followed the development of the technology at some level, but their main interests are elsewhere. Due to the current energy production mix in Finland, the absence of underground storage sites in Finland, the high costs and impaired energy efficiency, the deployment of CCS technology was seen as unrealistic in the near future. Hence we argue that deployment of CCS technology in Finland is framed with low expectations at the moment. However, there are differences in ways of framing the CCS issue in Finland.

Two general frames were identified. When the concerns of the stakeholders with a positive position on CCS were compared to the concerns of those with critical views, it seemed that the former are more concerned with issues related to costs, storage of CO_2 (absence of storage site) and policy and regulation issues, whereas the latter were concerned with environmental and health issues, investments (reduced investments in renewables due to CCS), public subsidies and technology issues (immaturity of CCS technology). We call the former as the ‘CCS development oriented’ frame and the latter as the ‘CCS sceptical’ frame.

8.2 CCS in the Finnish print media

In the study four temporal periods were identified based on the frequency of CCS-references in the Finnish press. The periods were as follows: (1) the period of nearly non-existent visibility (1996–2003), (2) the period of rising awareness (2004–2006), (3) the peak of attention (2007–2010) and (4) the period of decreasing interest (2011–2012).

In the first period (1996–2003) CCS was mentioned only few times in the Finnish press. First reference to CO_2 capture in the daily newspaper media was made in 1996 by the Finnish MEP Satu Hassi (the Green League) in her anti-nuclear energy tinged article in which carbon dioxide capture was portrayed in positive light, as an alternative to further investments to nuclear energy.

During the second period (2004–2006) awareness concerning CCS in the Finnish press was raised. As CCS was discussed in the international arenas the technology was also noticed in Finland. However, the terminology used about this particular topic is somewhat tenuous and unsystematic. The abbreviation CCS is yet nearly non-existent. Triggering events that spurred the articles around this topic include the Vattenfall Schwarze Pumpe CCS-plant investment in Germany and the UN climate conference in Montreal, the COP 11, in the end of 2005.

In the third period (2007–2010), the peak of attention, CCS-related discussion is substantial, summing to over 40 articles each year. The amount of articles published is nearly triple compared to previous years. Discussion is more vivid also in arguments and has more diverse portfolio of actors. International climate politics steps in with a bigger influence to the Finnish discussion as CCS finds its place in EU climate and energy policy. The growth in released articles can be explained by the increasing number of CCS-related events also in Finland, such as Meri-Pori retrofit project. Due to the plan several purely explanatory articles were released to explain and summarize the key points of yet widely unknown CCS-technology. Before 2007 CCS references in the Finnish press were short comments in wider climate political context, whereas from 2007 onwards articles solely concentrating to CCS technology start to appear in the newspapers. During the peak period attitudes towards CCS are mainly positive. Press attention forecast hope in the fight against climate change and new possibilities for coal energy. The German example of a carbon neutral coal plant and the Swedish and Norwegian announcements concerning future plans for carbon neutrality in their energy sectors are often referred to in the Finnish press.

The fourth period (2011–2012) is characterized by diminishing interest in CCS. The number of articles was much lower than in the peak years. The downward trend is surprisingly sudden and abrupt and clearly seen in the data. The most obvious reason for this was the cancellation of CCS-related projects in Europe. Also Meri-Pori project was discontinued, after which there were no deployable plans for CCS in Finland and therefore no domestic news to report in this field. Media interest decreased.

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Title	**CCSP Carbon Capture and Storage Program** **Mid-term report 2011–2013**
Author(s)	Sebastian Teir, Lauri Kujanpää, Marjut Suomalainen, Kalevi Kankkunen, Matti Kojo, Janne Kärki, Matti Sonck, Ron Zevenhoven, Sanni Eloneva, Kari Myöhänen, Matti Tähtinen, Timo Laukkanen, Kaj Jakobsson, Eemeli Tsupari, Toni Pikkarainen, Jessica Vepsäläinen, Antti Arasto, Esa Turpeinen, Riitta Keiski & Risto Sormunen (Eds.)
Abstract	Carbon Capture and Storage (CCS) is considered to be one of the main options for reducing global CO_2 emissions. However, the development of CCS technology faces many challenges. CO_2 capture is still very energy intensive and development is needed to bring costs down. Also, CO_2 needs to be transported to a suitable storage site for secure and permanent storage. Although CCS technology has not yet been implemented at a full-scale power plant, several demonstration projects are underway in the world. The report gives an overview of the work carried out in the Carbon Capture and Storage Program (CCSP) R&D program during 2011–2013. The R&D program is coordinated by CLEEN Ltd. with funding from Tekes – the Finnish Funding Agency for Technology and Innovation. The objective for CCSP is to develop CCS-related technologies and concepts, leading to essential pilots and demonstrations by the end of the program. A further objective is to create a strong scientific basis for the development of CCS technology, concepts and frameworks, and to establish active, international CCS co-operation. The program consortium consists of 9 research organisations and 17 industrial partners, with an annual budget of about 3 million euro per year. For Finland, CCS offers significant opportunities, which are being investigated and developed in CCSP. Being a large consumer of power and heat, Finland has a unique opportunity in integrating CCS with combined heat and power (CHP) plants. As Finland is a large consumer of biomass, adding CCS to bioenergy solutions (bio-CCS) would enable removal of CO_2 from the atmosphere. For heavy industry, such as oil refining and steel manufacturing, CCS is the only technology that can significantly reduce CO_2 emissions. For the Finnish technology developers and providers CCS could provide a significant market share in the future, such as in the area of oxy-fuel combustion and chemical looping combustion, which are being further developed in CCSP. Monitoring technologies is another quickly developing area where a growing Finnish expertise can help making CCS a safe and secure emission reduction and improve the social acceptance of CCS. As the Finnish bedrock does not have any formations suitable for underground storage of CO_2, other options are being investigated. A recent survey of the Baltic Sea area shows a potential for geological storage of CO_2. Several options for using CO_2 as a raw material for production of inorganic carbonates, chemicals and fuel components also show promise.
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Nimeke	**CCSP Carbon Capture and Storage Program** **Väliraportti 2011–2013**
Tekijä(t)	Sebastian Teir, Lauri Kujanpää, Marjut Suomalainen, Kalevi Kankkunen, Matti Kojo, Janne Kärki, Matti Sonck, Ron Zevenhoven, Sanni Eloneva, Kari Myöhänen, Matti Tähtinen, Timo Laukkanen, Kaj Jakobsson, Eemeli Tsupari, Toni Pikkarainen, Jessica Vepsäläinen, Antti Arasto, Esa Turpeinen, Riitta Keiski & Risto Sormunen (Toim.)
Tiivistelmä	Hiilidioksidin talteenotto ja varastointi on keskeisimpiä keinoja hillitä maailmanlaajuisia hiilidioksidipäästöjä. Kyseiseen teknologiaan liittyy kuitenkin vielä lukuisia kustannuksia lisääviä haasteita, joista keskeisenä on talteenottoprosessin korkea energiaintensiivisyys. Hiilidioksidi on myös kuljetettava pysyvään ja turvalliseen geologiseen varastointiin soveltuvaan sijaintiin. Hiilidioksidin talteenottoa ei ole sovellettu vielä täyden mittakaavan laitoksilla, mutta useita demonstraatioluokan projekteja on joko vireillä tai käynnissä maailmalla. Tämä raportti antaa yleissilmäyksen työhön, joka on tehty Carbon Capture and Storage Program (CCSP) -tutkimusohjelmassa vuosina 2011–2013. Ohjelmaa koordinoi CLEEN Oy. Teknologian ja innovaatioiden kehittämiskeskus Tekes on mukana rahoittamassa ohjelmaa. CCSP:n tarkoituksena on kehittää CCS:ään liittyviä teknologioita ja konsepteja, johtaen näistä keskeisimpien pilot-kokeisiin ja demonstraatioihin ohjelman loppuun mennessä. Tavoitteena on myös vahvistaa tieteellistä pohjaa CCS:n lainsäädännöllisen ja sosiaalisen viitekehyksen tutkimuksessa. Lisäksi ohjelman pyrkimyksenä on edesauttaa aktiivista ja dynaamista kansainvälistä yhteistyötä CCS:n saralla. Ohjelman konsortio koostuu yhdeksästä tutkimusorganisaatiosta ja 17 teollisuuspartnerista. Vuosibudjetti on n. 3 miljoonaa euroa. Hiilidioksidin talteenotto ja varastointi tarjoaa Suomelle merkittäviä mahdollisuuksia, joita tutkitaan ja kehitetään CCSP:ssä. Sähkön ja lämmön suurkuluttajana Suomella on ainutlaatuinen mahdollisuus soveltaa CCS:ää yhdistetyn sähkön ja lämmöntuotannon laitoksiin (CHP). Soveltamalla CCS-teknologiaa puolestaan Suomen moniin biomassaa polttaviin laitoksiin hiilidioksidia voitaisiin käytännössä poistaa hiilikierrosta ja siten ilmakehästä. Raskaalle teollisuudelle, kuten öljyn jalostukselle ja teräksen tuotannolle, CCS on ainoa teknologia, joka mahdollistaa voimakkaan hiilidioksidipäästövähennyksen. Suomalaiselle teknologiateollisuudelle CCS avaa markkinoita ja liiketoimintamahdollisuuksia uusien teknologisten ratkaisujen myötä. Näistä esimerkkejä ovat kemiallisiin hapenkantajiin perustuva polttoteknologia sekä happipolttoteknologia, joita kehitetään CCSP-ohjelmassa. Monitorointiteknologia on myös nopeasti kehittyvä alue, jolla kasvava suomalainen osaaminen voi parantaa CCS:n luotettavuutta ja turvallisuutta sekä myös edesauttaa teknologian julkista hyväksyntää. Suomen maaperästä ei kuitenkaan löydy soveltuvia geologisia muodostumia, joten ohjelmassa keskitytään muihin vaihtoehtoihin. Viimeaikaisen tutkimustiedon valossa Itämeren alueella on potentiaalia hiilidioksidin geologiseen varastointiin. Useat vaihtoehdot hiilidioksidin käyttämiseksi epäorgaanisten karbonaattien, kemikaalien sekä polttoaineiden valmistamisessa näyttävät myös lupaavilta.
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CCSP Carbon Capture and Storage Program
Mid-term report 2011–2013

The report gives an overview of the work carried out in the Carbon Capture and Storage Program (CCSP) R&D program during 2011–2013. The R&D program is coordinated by CLEEN Ltd. with funding from Tekes – the Finnish Funding Agency for Technology and Innovation. The objective for CCSP is to develop CCS-related technologies and concepts, leading to essential pilots and demonstrations by the end of the program. A further objective is to create a strong scientific basis for the development of CCS technology, concepts and frameworks, and to establish active, international CCS co-operation.

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