CARBON CAPTURE TECHNOLOGY OPTIONS AND THEIR FEASIBILITY FOR DIFFERENT EMITTERS

Lappeenranta–Lahti University of Technology LUT

Master's Programme in Sustainable Science and Solutions, Master's Thesis

2025

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Examiner: Associate Professor, Jouni Havukainen, D. Sc. (Tech.)

Supervisor: Ilari Ekman, M. Sc. (Tech.)

ABSTRACT

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Keywords: Carbon capture, CCS, CCU, EU ETS, carbon dioxide

This thesis aims to learn about carbon capture technologies and their market and assess the suitability and future of the market for carbon capture. The aim is to start exploring the technologies and the market with a view to future opportunities for the client company.

The thesis discusses the role of carbon dioxide in climate change and emissions trading. It identifies the largest emitting industrial sectors and the price of emissions trading per ton of carbon dioxide. Carbon capture technologies are also discussed to provide an understanding of the options for different emission sources and the variables that influence decisions. For existing plants, the main factors are the remaining lifetime of the plant and the level of purity and pre-treatment required for further treatment. For new plants, the main factor seems to be the location close to a recovery or storage site or good transport connections.

When the market for carbon capture and the costs of plants were examined, as investment/operating costs were calculated for different power plants, the investment and operating costs were still too high for a larger market opening. However, it should be noted that the profitability of carbon capture will in the future be determined by both the price per emission ton of carbon dioxide and the price of carbon dioxide as a product. The biggest problem with investments is still the lack of storage capacity and usage as merchandise. If policy guidance is given, the capture market will quickly become active and provide jobs for many.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT

LUTin energiajärjestelmien tiedekunta

Ympäristötekniikka

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Tarkastaja: Apulaisprofessori Jouni Havukainen (TkT)

Ohjaaja Ilari Ekman (DI)

Avainsanat: Hiilidioksidin talteenotto, CCS, CCU, EU ETS, hiilidioksidi

Työn tavoitteena on tutustua hiilidioksidin talteenottoteknologioihin sekä markkinaan sekä arvioida markkinoiden sopivuutta ja tulevaisuutta tilaajayhtiölle. Tarkoituksena on aloittaa teknologioiden ja markkinoiden tutkiminen tilaajayrityksen tuleviin mahdollisuuksiin liittyen.

Työssä käsitellään hiilidioksidin roolia ilmastonmuutoksessa, päästökauppaa ja etsitään päästöiltään suurimpia teollisuuden sektoreita sekä päästökaupan hintaa hiilidioksiditonnille. Myös hiilidioksidin talteenoton teknologiat käydään läpi, jotta saadaan ymmärrys vaihtoehdoista eri päästölähteille sekä päätöksiin vaikuttavista muuttujista. Näistä suurimmaksi tekijäksi muodostuu olemassa oleville laitoksille niiden jäljellä oleva käyttöikä sekä jatkokäsittelyn vaatima puhtaustaso ja esipuhdistus. Uusille laitoksille suurimmaksi tekijäksi näyttää tulevan sijainti hyötykäyttö- tai varastointipaikan läheisyydessä tai hyvät kuljetusyhteydet.

Kun tutkittiin hiilidioksidin talteenoton markkinoita ja laitosten kustannuksia, laskettu muutama investointi/käyttökustannus erilaisille voimalaitoksille, havaittiin investointien ja käyttökustannusten olevan vielä liian korkeita markkinoiden suuremmalle avautumiselle. Huomioitavaa on, että hiilidioksidin talteenoton kannattavuus määräytyy jatkossa sekä päästökaupan hiilidioksiditonnin hinnan että hiilidioksidille tuotteena muodostuvasta hinnasta. Suurin ongelma investoinneissa on vielä varastointikapasiteetin ja hiilidioksidin hyötykäytön puute. Jos poliittinen ohjaus toteutuu, talteenotto markkinat aktivoituu nopeasti ja tarjoaa töitä monille.

KIITOKSET

Haluan kiittää työn tilaajayritystä tästä diplomityömahdollisuudesta sekä tuesta, jota yrityksen työystävät ovat antaneet. Haluan kiittää myös ohjaajiani Jouni Havukaista sekä Ilari Ekmania ajasta, neuvoista sekä tuesta ja kommenteista koko syksyn ja talven ajalta.

Haluan lisäksi kiittää perhettäni ja ystäviäni antamastanne tuesta niin opinnoissa kuin diplomityön aikana.

SYMBOLS AND ABBREVIATIONS

Roman characters

C	cost	€/t_{CO2}, M€
E	energy input	MWh/a
q_m	mass flow	kg/s
i	interest rate	%
j	emission coefficient	t_{CO2}/GJ, kg/MW
m	mass	kg
n	lifetime	
s	scale factor	
t	time	h, s
P	Power	MW
V	gas flow	Nm^3/s

Greek characters

η	efficiency	%

Subscripts

a	annual
cc	carbon capture
f	fuel
h	peak operating time
ref	reference
total	total amount
th	thermal fuel power

Abbreviations

BECCS	Bioenergy with carbon capture and storage
CAPEX	Capital Expenditure
CC	Carbon Capture
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CEF	Connecting Europe Facility
CEF-E	Connecting Europe Facility Energy
DAC	Direct Air Capture
EEA	European Environment Agency
EOR	Enhanced Oil Recovery
ETS	Emissions Trading System
EU	European Union
GHG	Greenhouse Gas
GWP	Global Warming Potential
HPC	Hot Potassium Carbonate
IGCC	Integrated Gasification Combined Cycle
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land Use, Land-use Change and Forestry
OPEX	Operating Expenditure
PCC	Post-combustion Capture
PCI	Projects of Common Interest
PMI	Projects of Mutual Interest
P2X	Power-to-X

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Appendix 1. Customer Survey questions

1 Introduction

Material burning is called combustion, a chemical process where a substance reacts quickly with oxygen. For combustion to happen, there must be three things: fuel to burn, a source of heat, and a source of oxygen. Combustion releases heat from the fuel's chemical energy and at the same time produces flue gases. (NASA 2021)

Flue gases consist of chemical substances and due to high temperatures, the flue gas is usually in gas form. There can be solid or liquid substances, which will be emitted into the atmosphere after combustion. Some of the flue gas substances are called emissions, which cause local and global phenomena in the Earth's atmosphere causing global warming. (NASA 2021; McGrath & Jonker 2023)

The primary contributor to global warming is greenhouse gas emissions (GHG). GHG emissions specifically mean the release of particular gases that cause the increased greenhouse effect. The greenhouse effect, essential to keep Earth warm enough, prevents heat from escaping back to space. The main greenhouse gases are carbon dioxide CO_2, methane CH_4, Nitrous oxide N_2O, and fluorinated gases. Although natural causes can produce GHG emissions, most are caused by human activities, from burning fossil fuels to transportation and energy production. (McGrath & Jonker 2023)

Greenhouse gases have increased rapidly since the Industrial Revolution, causing more heat to be trapped, and increasing the global temperature. It is estimated that human activities have caused a global warming of 1.1℃ compared to the pre-industrial levels. If the current rate continues, warming will increase to 1.5 ℃ between 2030 and 2052. This warming has caused climate and weather extremes across the world. It has negatively impacted water and food security, society, the economy, and human health, as well as much damage and losses to people and nature. The most vulnerable communities are hugely affected by the warming. If global warming crosses 2 ℃, the impacts can be irreversible. There is a clear need to change existing behaviour to reduce GHG emissions. (IPCC 2018; IPCC 2023)

Since carbon dioxide is the most significant human-produced greenhouse gas, the most effective way to reduce GHG emissions is to lower the CO_2 emissions (OFS n.d.). Combustion always produces CO_2 emission, for example, when a hydrogen-carbon-based

fuel, such as coal, is burned the flue gas contains mostly water and carbon dioxide (NASA 2021). In other words, to reduce emissions, burning should be reduced, especially using fossil fuels, or removing CO_2 from flue gas, because not all industries such as the cement industry can be fully decarbonized. These could be utilizing more climate-friendly fuels, biofuels, and carbon capture, CC. (McGrath & Jonker 2023; Crable 2024)

Biofuel is a fuel produced over a short period from biomass rather than by the very slow natural processes involved in forming fossil fuels such as oil. Biofuels are made from biomass such as plants, animal waste, algae material, or industrial biowaste. (Itskos et al. 2016; Lehman & Selin 2018)

Carbon removal happens naturally on Earth with trees and oceans being big carbon removers. Unfortunately, they cannot meet human demand and remove all CO_2 emissions. Even if CO_2 production stops, there will still be CO_2 in the atmosphere, which would affect the atmosphere. Carbon capture technologies must be implemented to achieve the goal of limiting global warming to 1,5 °C. These technologies are called carbon capture, CC, where man-made CO_2 from the atmosphere or point source is prevented from contributing to climate change. (Crable 2024; Carbon Capture n.d.)

As carbon capture is quite new, no commercial large-scale, viable technologies are ready to be used. The technologies have been developed, but they are still in the early stages. In addition, there is not a big enough market for the further use of carbon dioxide, and therefore no price and no value for money for the CO_2 captured. However, carbon capture could have huge potential for technology providers and developers, so it has been explored. (Dziejarski et al. 2023)

1.1 Objectives of the Work

The main focus of the thesis is on carbon capture, as well as going over the basic idea of further processing, i.e. CCU and CCS. The idea of doing this is to look for various carbon capture-related technologies from literature and interviews.

The thesis aims to understand the readiness and suitability of technologies for commercial industry-level usage. Since the client of this thesis works with power plants and their flue gas treatment technologies, the studies focus more on the combustion-related industry. So, one purpose is to map the suitability of technologies for different combustion technologies and fuels. The aim is to identify quality requirements, size classes, technology maturity, and price, which means understanding the applicability of different technologies to different emission sources. For example, Direct air capture, DAC, is a technology where CO_2 is taken directly from the atmosphere and this thesis does not go into depth with DAC.

In addition to the introduction, this thesis consists of a theory part, followed by a comparison of different technologies and market and case studies. The theory part is divided into four main chapters. The theory chapters address emission sources and carbon capture process technologies. The actual CC, CCU, and CCS process descriptions are divided into subchapters. The fourth chapter gives a brief introduction to the current carbon capture projects. After the theory part, the fifth chapter gives insight into the differences in carbon capture technologies, utilizing the knowledge gained in the third chapter. This is followed by a market and a case study to apply the theory.

The conclusion chapter summarizes the whole study, explaining the findings of the thesis and providing answers to the research questions.

2 Carbon Capture Drivers and Policies

The European Union (EU) launched an emissions trading system (EU ETS) in 2005 to limit carbon dioxide emissions. Emissions trading aims to reduce GHG emissions from energy, industrial production, and aviation within the European Economic Area. (European Commission 2020; The Ministry of Economic Affairs and Employment n.d.) The European Union (EU) has committed to reach net-zero emissions of CO_2 by 2050. A significant part of this goal will be done by reducing the number of current emissions sources, but CO_2 capture technologies are also needed. These technologies especially help reduce emissions from sectors with difficulties reducing emission sources. (European Commission 2024)

In Europe, large industrial plants are already covered by emissions trading, the effectiveness of which is mainly based on the price of carbon dioxide emissions. In emissions trading, the emitter pays for the tons of CO_2 it emits. The idea is that industrial operators buy and sell the emission allowances they need in tons of CO_2 to determine the price per ton of CO_2. In this way, the sectors concerned have been steered towards reducing the burning of fossil fuels and have been persuaded to choose more climate-friendly options. (The Ministry of Economic Affairs and Employment n.d.; European Commission 2016)

However, this model does not include carbon sinks, which would be a good option to speed up climate actions. This would imply a similar crediting/compensation mechanism for capture so that negative CO_2 emissions could be compensated. If the technologies and their price were to develop rapidly, there could even be commercial value for captured CO_2 in a voluntary market. (Carbon Gap n.d.; Vantaan Energia 2024)

Drivers and policies play a major role in achieving the objectives and making carbon capture more mature technology. Drivers are factors that can influence the achievement of the desired objectives. In this case, things that influence the growth and development of carbon capture. (Ministry of Environment n.d.; Hayes 2023)

One of the biggest drivers of carbon capture is environmental awareness of degradation. The awareness of the impact of CO_2 emissions on the climate leads to commitments and practices that drive different carbon capture projects forward. (ELY-keskus 2024)

Another big driver for carbon capture is new CO_2 utilization methods, such as synthetic fuels or plastic processing. Synthetic fuels could be produced by combining captured CO_2 and hydrogen from electrolysis, where renewable energy separates water into H_2 and O_2 molecules. H_2 is then led to react with CO_2 captured from the process, and this methanation process converts it to methane. In plastic production, the captured CO_2 could be used as a part of the manufacturing process to form different hydrocarbons, which then serve as raw materials for plastics. (REPSOL n.d.; Pires da Mata Costa et al. 2021)

One hindering factor for CO_2 removal is the price per ton of CO_2, which is not globally noted. Another slowing factor is the immaturity of carbon capture technologies, and to some extent, carbon purity standards are also slowing the process, so stronger leverages such as policies are needed. Many environmental objectives are achieved via policies. The policies can promote innovations and help develop the old ones; thus, they can be seen as a driving force. (Gonzales et al. 2023; Patanakul & Pinto, 2014)

Energy demand and climate targets have increased, increasing the need for carbon management technologies. Therefore, policies are needed to manage the technologies safely. (European Commission n.d.a)

Carbon capture does not generate revenue or market benefits if CO_2 has no price. It costs a lot to install and operate carbon capture. Comprehensive policies help carbon capture overcome the barriers by minimizing investment risks and promoting carbon capture deployment. European commissions approved a legislative proposal for the certification of carbon removals. It sets rules for monitoring, measuring, verifying, and reporting CO_2 removals. Most of the policies about the technologies are meant for storing part of carbon capture. (IEA 2012; Global CCS Institute n.d.)

If the price of a ton of CO_2 remains globally low, or alternative fuels are not sanctioned, there will be no interest in new technologies and no incentive to invest in them. Adding CO_2 capture to EU ETS could help. The negative carbon emissions could be accounted for in the future EU ETS. Carbon capture has already benefitted from EU ETS via funding. (Carbon Cap n.d.; Levina et al. 2023)

Funding is also an important part of promoting carbon capture. Funding provides support and resources for carbon capture, including resources for research and development and help with scaling it up to market. There are many kinds of funds for different technologies. Funds

for carbon capture in the EU are the Innovation Fund, Connecting Europe Facility, and Horizon Europe. (Faster Capital 2023; Levina et al. 2023)

The EU Innovation Fund funds the commercial implementation of decarbonization technologies. It is financed from EU ETS revenues and depending on carbon prices, the amount of money can reach €40 billion in 2020-2030. The Innovation Fund launched a third call for proposals from November 2022 to July 2023 for innovative clean projects. 41 projects were chosen for this call, and 10 were related to CCS or CCU. (European Commission n.d.b; Levina et al. 2023)

Connecting Europe Facility, (CEF) funds the development of efficient and sustainable trans-European energy, transport, and digital services projects. Carbon capture can get funding from the energy part of CEF, CEF-E. In CEF-E the projects can be funded as Projects of Common Interest (PCI) or Projects of Mutual Interest (PMI), and most of the carbon capture projects have been financed as PCIs. The energy projects that promote the building of energy infrastructure between EU countries are called PCI. PMIs are similar projects, but they involve cooperation with countries outside of the EU. (European Commission n.d.c; Energiavirasto 2023) The CEF for Energy has a budget of €5.84 billion for 2021-2027, and four carbon capture projects have received a total of €480 million. (European Commission 2023b.)

Horizon Europe is a funding program for innovation and research. This funding program aims to strengthen and facilitate cooperation in research and innovation that combat climate change. The budget for funding is €95.5 billion from 2021 to 2027. (Blanchard 2024)

Environmental licensing policies will certainly be another way to increase the development and potential of carbon capture. In this case, new energy and industrial plants would be obliged to integrate CO_2 capture into their process immediately. After a transition period, existing plants could also be obliged to increase carbon capture. These drivers and policies have a huge impact on man-made emissions, although only in Europe, as they apply to energy and industrial processes. Together they account for more than 50 % of anthropogenic CO_2 emissions in Europe. (SYKE and Ministry of Environment 2023; EDGAR 2023)

3 The Role of Carbon Dioxide in Global Warming

Carbon is constantly circulating in different forms on Earth. The natural cycle of carbon in the atmosphere as carbon dioxide is fast, while the impact of man-made carbon dioxide in the atmosphere is much longer. (Finnish Meteorological Institute 2024a)

As new carbon dioxide is created, the carbon cycle distributes it between the atmosphere, vegetation cover, and oceans. Oceans, vegetation, and soil act as carbon sinks for the atmosphere. According to the studies from the IPCC, an estimated 45% of all carbon dioxide that humanity has spewed into the air from the 1700s to the present day has remained in the atmosphere. (Finnish Meteorological Institute 2024a)

Plants bind carbon dioxide from the atmosphere because it is needed for photosynthesis which produces oxygen for humans, which is vital for life. This bound carbon is released back into the atmosphere as carbon dioxide as a by-product of cellular respiration of plant cells and animals. In addition, carbon dioxide is naturally formed in volcanic eruptions, and by combustion. (Biology Online 2022; NETL n.d.a)

CO_2 is one of the components that is needed to create conditions where plants, animals, and humans can live, the greenhouse effect. The greenhouse effect is when the heat radiation from sunlight does not escape back into space but is reflected to Earth by the atmosphere. Without it, the average temperature of Earth would be around -20 °C. This would also mean that water would freeze and life on Earth would not be the same as now. (British Geological Survey 2022; University of Galgary 2024)

Although CO_2 does not have the highest global warming potential (GWP), the ability to absorb heat, CO_2 is the largest man-made greenhouse gas. It has contributed to the increase of the greenhouse effect greatly, among other things, the rising of the average temperatures, melting ice and snow, the extinction of plants and animals, and changes in water acidity. It could be said that the man-made combustion of fossil fuels has led to climate change. (Budinis 2024; Myclimate n.d.)

Humans have burned fossil fuels for transportation, energy, and various production plants. It started with the coal-fired steam engines in the 1700s and accelerated with the Industrial

Revolution. The industry still needs the fuel's chemical energy in their processes to produce energy in its various forms (University of California Museum of Paleontology, 2024)

As the manufacturing industry is still partly dependent on combustion, partly even fossil fuels, it is very clear that the release of carbon dioxide into the atmosphere must be limited or removed. The means for limiting CO_2 include putting a price on carbon dioxide, shifting faster to carbon-cycling biofuels or other recyclable waste, and synthetic fuels. The options for removing the carbon dioxide are capturing CO_2 directly from the air, DAC, or a point source, carbon capture (CC). (Eesi 2021; Global CCS Institute 2024)

3.1 Biggest Industry Sectors in CO_2 Emissions

In 2015, the Paris Climate Agreement was signed to limit the average temperature rise to 1.5 °C compared to pre-industrial times. By the end of 2021, the agreement had been signed and accepted by 191 parties, covering 97 % of GHG emissions. Key elements of the agreement include the obligation for Parties to develop Nationally Determined Contributions (NDCs) to communicate their adaptation and reduction targets and to report on their planned climate actions. For parties to decide on their targets, current emissions must be known. (Ministry of Environment 2023)

In 2022, the total anthropogenic fossil carbon dioxide emissions accounted for 38.5 gigatons. The majority, 38% of emissions come from the energy industry. The second largest source of emissions is industrial combustion 25%. And the third largest is transportation 20.7%. Emissions from buildings account for 8.9 % and fuel production 6.6%. Agriculture and waste are the lowest emitters, with agriculture accounting for 0.39% and waste at 0.04%. Carbon dioxide emissions by the sector are shown in Figure 1. (EDGAR 2023)

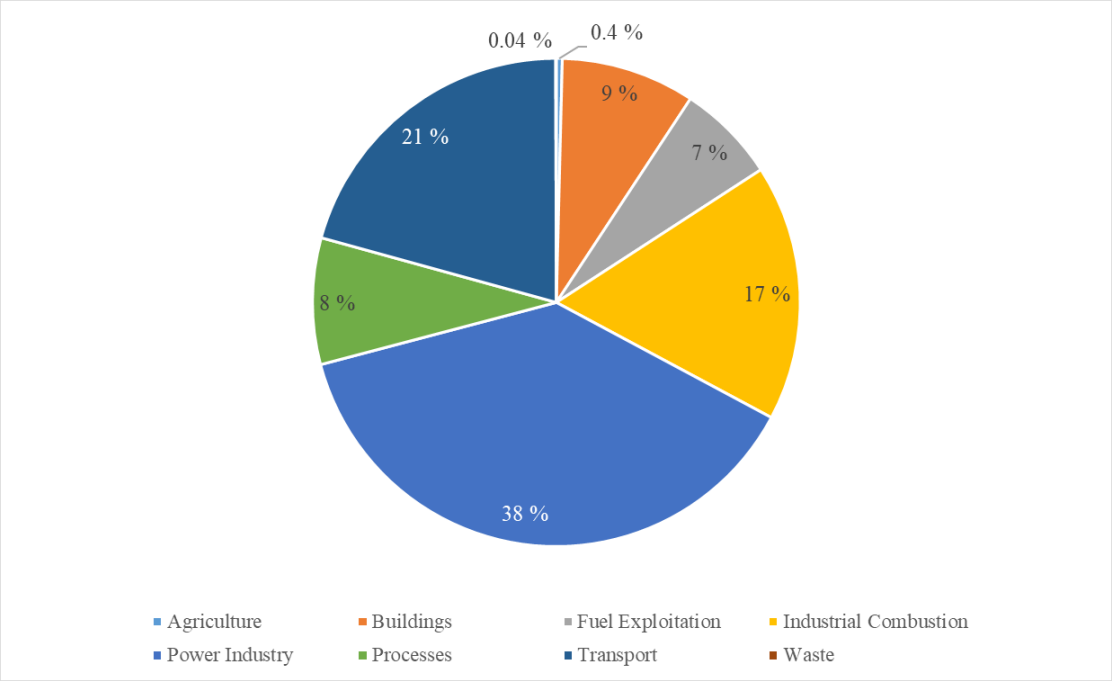

Figure 1. World's CO_2 Emissions in 2022 (EDGAR 2023)

Most of these emissions come from burning fossil fuels, which are mainly hydrocarbons. The complete combustion reaction of fossil fuels produces carbon dioxide CO_2, water H_2O, and energy. The only exception is carbon C, as its complete combustion does not produce water. The combustion reactions of carbon C, and methane CH_4 are shown in equations 1 and 2. (Statista 2024c; ESA pyronics n.d.)

$$C + O_2 \leftrightarrow CO_2 \quad (1)$$

$$CH_4 + 2\,O_2 \leftrightarrow CO_2 + 2\,H_2O \quad (2)$$

In 2020, the EU committed to reduce net GHG emissions, which include carbon sinks, by at least 55% by 2030 compared to 1990. In addition, the EU has another target, including the EU Climate Change Act, to be climate-neutral by 2050. By doing this, it would result in a net carbon sink at the EU level. That is why the EU needs to keep track of their emissions. (Ministry of Environment 2023)

In 2022, the total anthropogenic fossil carbon dioxide emissions accounted for 2.88 gigatons. The majority, 30.7% of emissions come from the energy industry. The second largest source of emissions is domestic transportation 27.8%. And the third largest is industry 21.1%.

Emissions from buildings account for 13.4% and international aviation 2.8%. Other combustion accounts for 2.8% of CO_2 emissions. Agriculture and waste are the lowest emitters, with agriculture accounting for 0.3% and waste at 0.1%. Carbon dioxide emissions by the sector are shown in Figure 2. (Tiseo 2024)

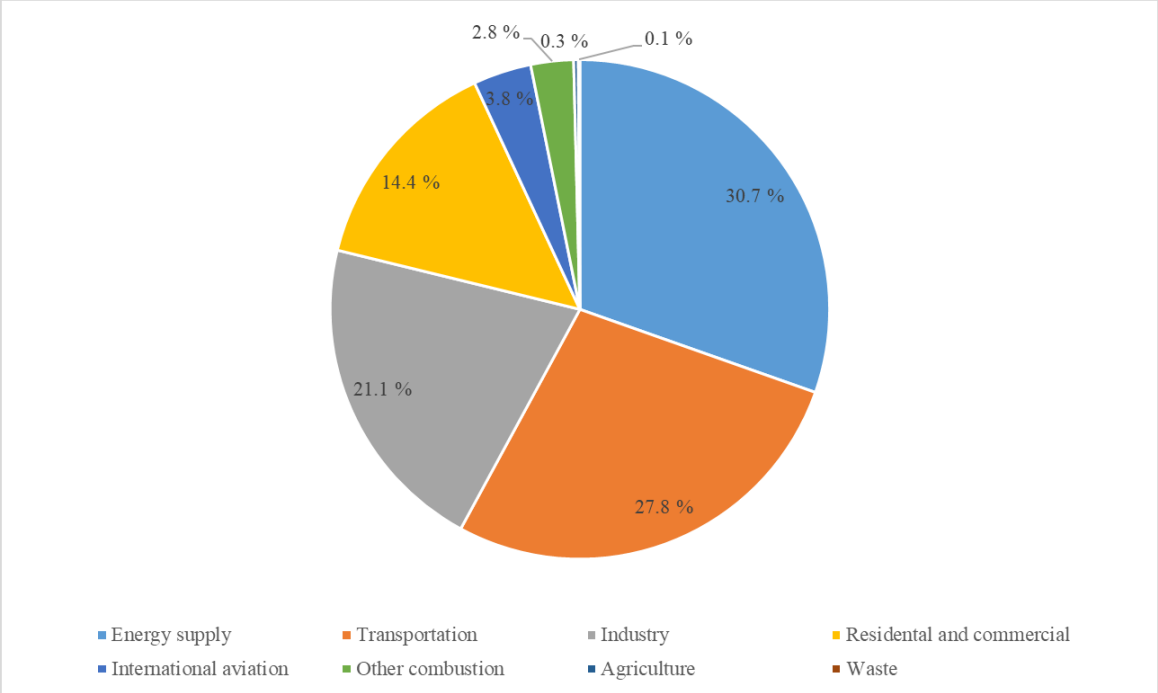

Figure 2. EU's CO_2 Emissions in 2022 (Tiseo 2024)

Finland's revised Climate Change Act entered force in 2020, setting a carbon neutrality target by 2035. The emission reduction targets for 2030 are -60 % and by 2050 -95 % compared to 1990. The aim is also to increase the amount of carbon sinks. (Ministry of Environment 2023)

Total GHG emissions, including biogenic and fossil fuels, in 2022 in Finland were 50.5 megatons CO_2-eq. Of these, about 80 % are carbon dioxide emissions, or CO_2 emissions, which were around 40.4 megatons in 2022. 65 % of these emissions came from the energy industry, 10 % from industrial combustion, 12 % from agriculture, 9 % from LULUCF, and 3% from waste. The sector division in Finland differs from that of the world data. (OFS 2022; European Parliament 2023)

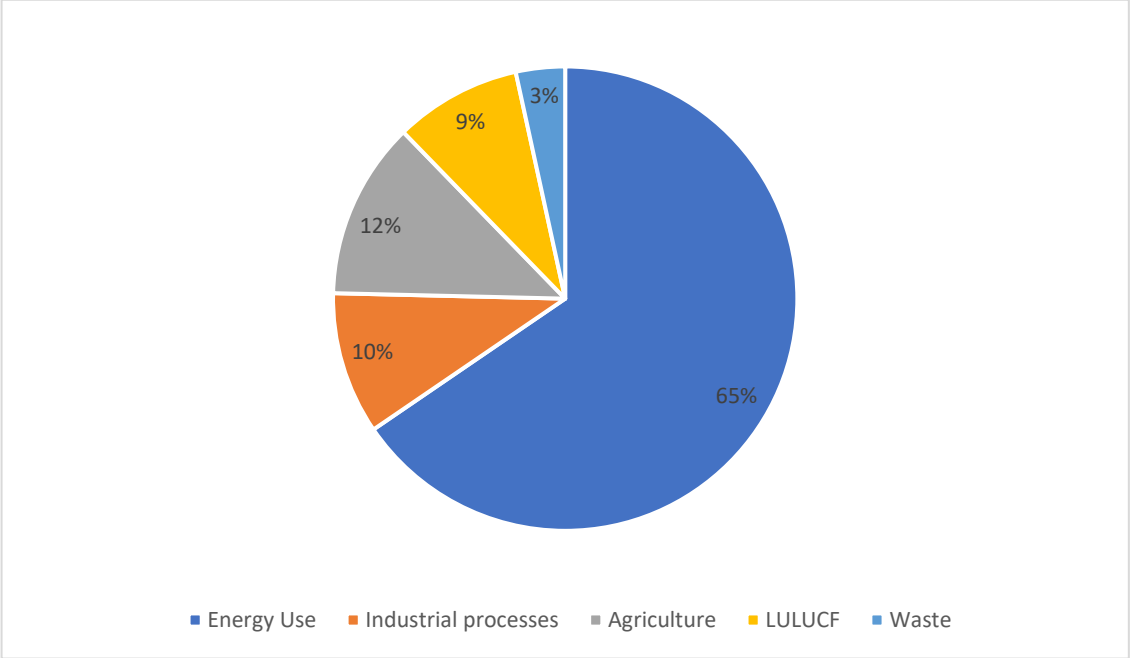

Figure 3. Finland's Emissions in 2022 (OFS 2022)

As seen from the previous figures, the energy industry and industrial processes have high emissions, and most of the emissions from these sectors come from burning fossil fuels. Around 80 % of the world's energy and around 65 % of industrial processes are fossil fuel-based. (Eesi 2021; IEA 2023) In waste management, non-recyclable solid waste is incinerated, responsible for most CO_2 emissions from waste treatment. The energy industry and industrial processes have sought to reduce CO_2 emissions by reducing the use of fossil fuels and switching to more environmentally friendly alternatives such as wind power and combustion with biomass, biofuels, and hydrogen as well as energy recovery from waste. (Eesi 2021; Ramboll 2023)

However, the shift does not eliminate emissions as all combustion, except burning hydrogen, produces carbon dioxide emissions. Biofuel emissions, like wood burning, are seen as carbon neutral because the carbon dioxide released is more quickly sequestrated back into the growing biomass. However, recent studies have shown that burning biomass can also have significant climate and health impacts. (Jiang et al. 2024)

Waste incineration can sustainably serve as the last stage in the life cycle of products. It should be reduced in any case, as waste management involves incineration of non-recyclable solid waste, which causes CO_2 emissions. (Ramboll 2023)

To address the current emission situation, various combustion substitutes are constantly being studied and developed, but until they are ready and of course after that, an intermediate step could be carbon capture at sites where carbon dioxide emissions cannot be prevented. This means that the greatest potential for carbon capture lies in sectors with high CO_2 emissions that are difficult to reduce by only limiting fossil fuel use or improving energy efficiency, meaning sectors where combustion processes mainly generate emissions and are difficult to replace by other means. These sectors include the energy industry, industrial processes, and waste treatment. (European Commission 2023a; Bundinis et al. 2023)

Carbon capture is already being researched and developed in the energy industry, mainly in existing plants that run on coal and natural gas, but they are not yet very profitable for their owners. In industrial processes, carbon capture is in widespread commercial use in processes such as CO_2 gas production, fertilizer production, and natural gas processing including hydrogen production, coal gasification, and ethanol production. (C2ES n.d.)

4 Carbon Capture, Storage, and Utilization

There has been a shift to more sustainable solutions to decarbonize the power and industrial sectors, mainly by switching to renewable fuels that also produce CO_2 when burned, only with a faster carbon cycle. However, there are geographical and process constraints with substitute energy sources, making reducing CO_2 emissions more challenging and time-consuming. In such cases, carbon capture would be a good tool, but it is still in its early stages of development and not yet techno-economically viable. It will play a major role in a low-carbon future as it becomes more efficient. (Gordon 2023; NREL 2019)

4.1 Main Carbon Capture Options

A technology, currently in the early stages, of taking CO_2 from the air is called direct air capture (DAC), where carbon capture happens by blowing air with large fans into a carbon dioxide filter. A binding sorbent is added to the filters so the carbon dioxide will be trapped, and the other components of air will continue their journey. CO_2 is separated from the filters by heating, then the sorbent will be separated from the CO_2, and CO_2 is passed on to further purification. (Budinis 2024; Climeworks n.d.)

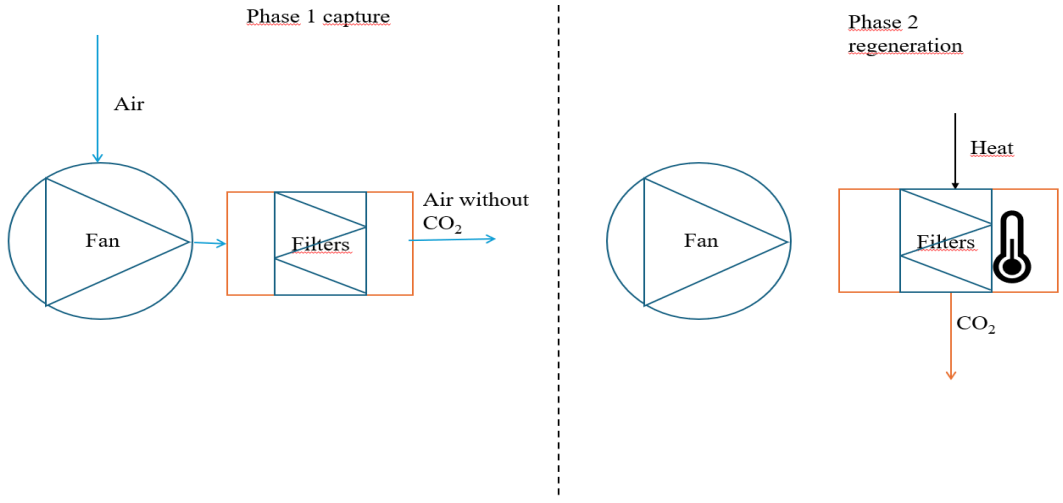

Figure 4. Direct Air Capture (Modified from Beuttler et al. 2019)

Carbon capture technologies related to combustion processes can be divided into three categories, depending on the type of arrangement and the stage of the process at which CO_2 is captured. These three combustion carbon capture technologies are pre-combustion, post-combustion, and oxyfuel-combustion capture. All these technologies include several separation techniques, and these technologies are developed for the capture of CO_2 emissions from point sources i.e. facilities such as power plants or industrial processes. The chosen method depends on many factors such as the plant design, process, and costs. These technologies focus on CO_2 but perhaps could also capture compounds such as nitrogen oxides, hydrogen, sulfur dioxide, and particulate matter. (Global CCS Institute 2024; NETL n.d. b)

4.1.1 Pre-combustion Capture

Pre-combustion capture removes CO_2 before the final combustion process takes place. In this technology, it is possible to choose either air or oxygen for combustion. If air is chosen, a NO_x removal system must be added. If oxygen is chosen, an air separator unit is required to separate oxygen from air and remove nitrogen before the process. (NETL n.d. b)

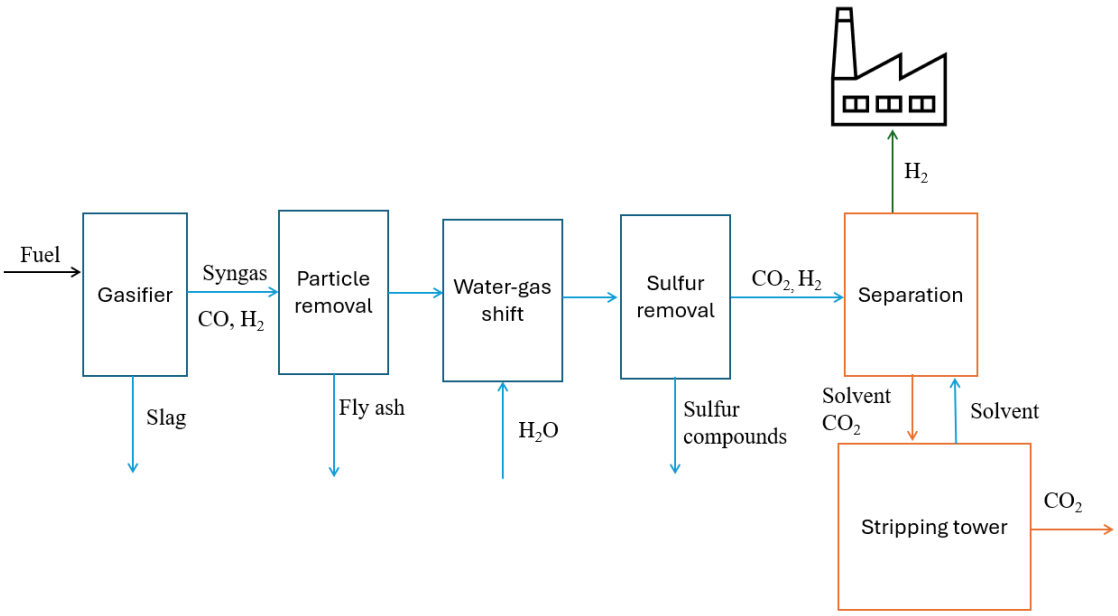

Figure 5. Pre-combustion Capture (Modified from Teir et al. 2009)

In the process shown in Figure 5. fuel, and oxygen, separated from the air, are fed into a gasifier. In the gasifier, the amount of oxygen is kept so low, 20-30 %, that only partial combustion occurs. This sustains the reaction and produces enough heat to break down the fuel and chemically produce syngas. A gasifier gasifies the fuel, under reduced oxygen and pressure, into syngas, a mixture of carbon monoxide CO, hydrogen H_2, methane CH_4, and carbon dioxide CO_2. The syngas also contains small amounts of other gaseous components. (Teir et al. 2009; NETL n.d. b)

Slag and solid matter are removed from the gasifier, and then the syngas is passed on to a fly ash remover, such as a cyclone. From the cyclone, the syngas continues through the water-gas-shift reactor, where CO is converted to CO_2 with water. The added water causes the CO in the syngas to react, producing CO_2 and more H_2. The water gas shift causes the partial pressure of CO_2 to rise to a high level, which improves CO_2 separation techniques efficiency. (NETL n.d. b; NETL n.d. c)

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad (3)$$

After the shift sulfur compounds are removed from the syngas with a desulfurizer (sulfur removal) washing the syngas upstream and removing sulfur from the process. The syngas continues from here to the carbon dioxide separator (in this case absorption separator), the CO_2 scrubber, and the stripper, where CO_2 and further usable H_2 are separated. The separated CO_2 is dried and put into further processing or storage. After separation, H_2 can be used for combustion or as a feedstock for the chemical industry. (Teir et al. 2009; NETL n.d.b)

4.1.2 Post-combustion Capture

In post-combustion capture, CO_2 is captured after the combustion process. This is probably the easiest technology to add to existing combustion plants as a stand-alone unit. In the Figure 6 process diagram, the power plant process, fuel is combusted by using air as a source of oxygen in a boiler. The boiler converts the combustion energy into water vapor, then fed into a steam turbine, which converts the steam energy into electricity in a generator. (NETL n.d. b)

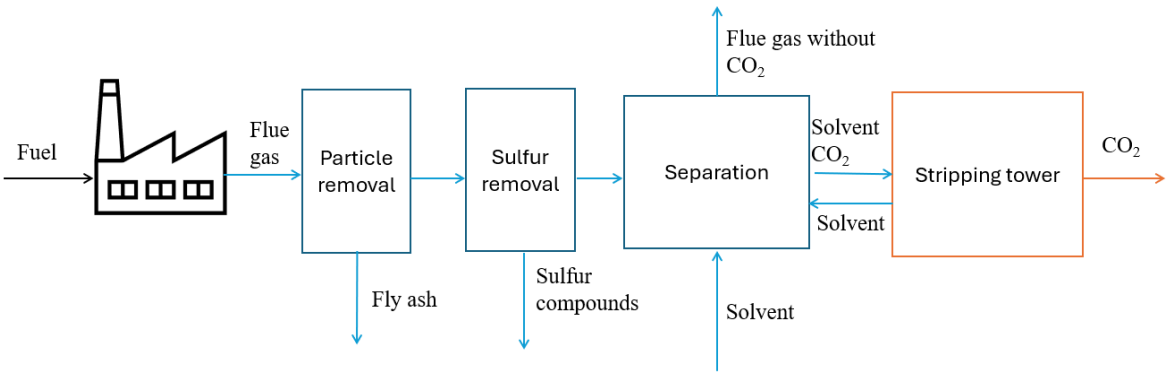

Figure 6. Post-combustion Capture (Modified from Teir et al. 2009)

The flue gases from the combustion process are directed first to nitrogen removal (selective catalytic reduction) usually located in the boiler. From the boiler, the flue gas is routed through the flue gas duct to the particulate separator (cyclone, electrostatic precipitator, bag filter) and from there to the sulfur removal (scrubber). These must be removed, otherwise, they will react with the separating solvent, causing solvent deterioration. After the sulfur removal of the flue gas, the temperature must be brought to the correct range for the CO_2 scrubber 30-40 °C. This is achieved either by heat recovery technology connected to the scrubber or by a separate cooler. (Teir et al. 2009; Koons 2023)

The cooled flue gas is then fed to a separation unit, where CO_2 is separated from the flue gas. The separation unit can consist of many parts depending on the separation technique. From the separation unit, the CO_2 is captured for further processing. (NETL n.d. b; Khalid et al. 2022)

4.1.3 Oxyfuel-combustion Capture

In oxyfuel-combustion capture, CO_2 capture is similar to post-combustion capture, which means that CO_2 is separated after combustion. But instead of air, combustion happens with pure oxygen extracted from the air. This requires an air separation unit before combustion. In oxyfuel combustion capture the fuel reacts with pure oxygen to form flue gases containing only CO_2, H_2O, SO_2, and particulates. Particulates are normally removed by particle separation techniques and sulfur with a scrubber. Afterward, the flue gas is further condensed

by a cooler/condenser, whereby water condenses and is separated from the flue gases. From here, the separated CO_2 is recovered for further treatment and the condensate accumulated at the bottom is removed as water from the process. The steam process is the same as in the post-combustion capture process. The combustion and its temperature can be controlled, if necessary, by recirculating the flue gases after particle separation on the oxygen line to replace the oxygen. The process can be seen in Figure 7. (Khalid et al. 2022; Nanda et al. 2016)

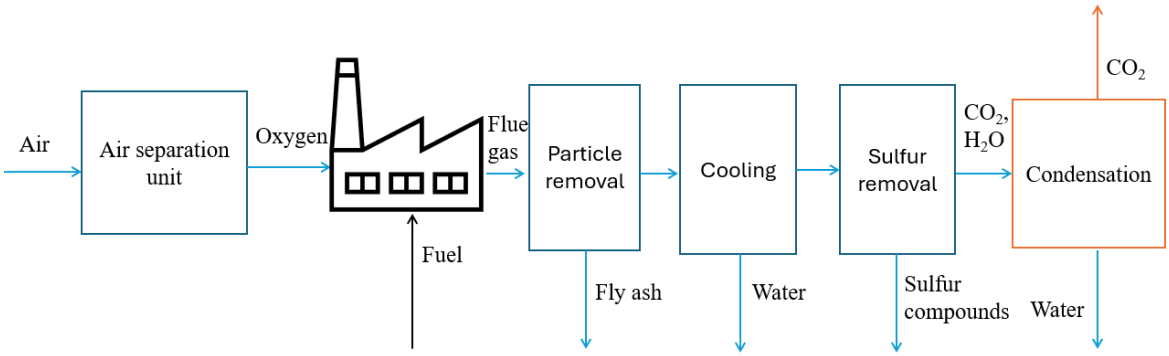

Figure 7. Oxyfuel-combustion Capture (Modified from Teir et al. 2009)

4.2 Description of Carbon Capture Separation Techniques

Carbon capture technologies use different separation techniques, as there are several ways to separate CO_2 from flue gas. The techniques include absorption, adsorption, cryogenic distillation, membrane separation, gas hydrates, and chemical looping. (Leung et al. 2014)

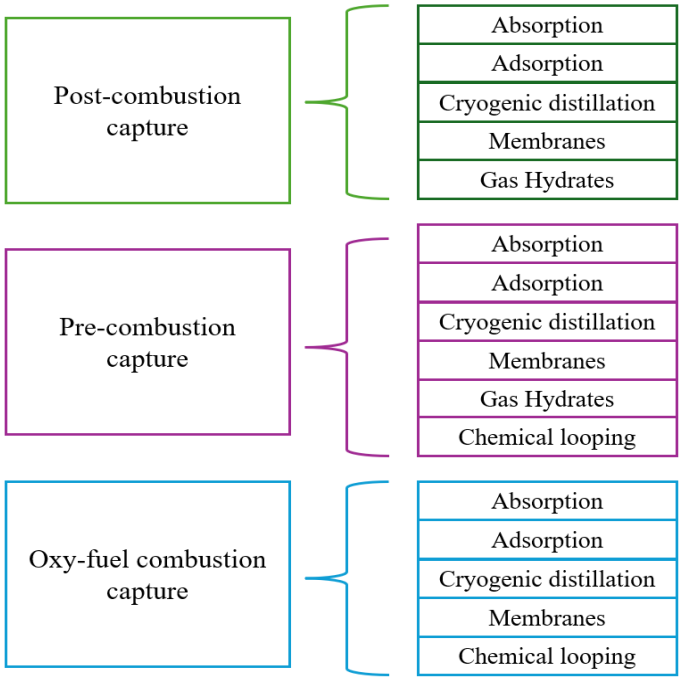

Figure 8. Separation Techniques (Modified from Patil et al. 2022)

4.2.1 Absorption

In absorption, CO_2 is separated using a liquid sorbent. Typical sorbents are amine-based solvents and hot potassium carbonate. The absorption is presented below. (Leing et al. 2014; GCCA 2025a)

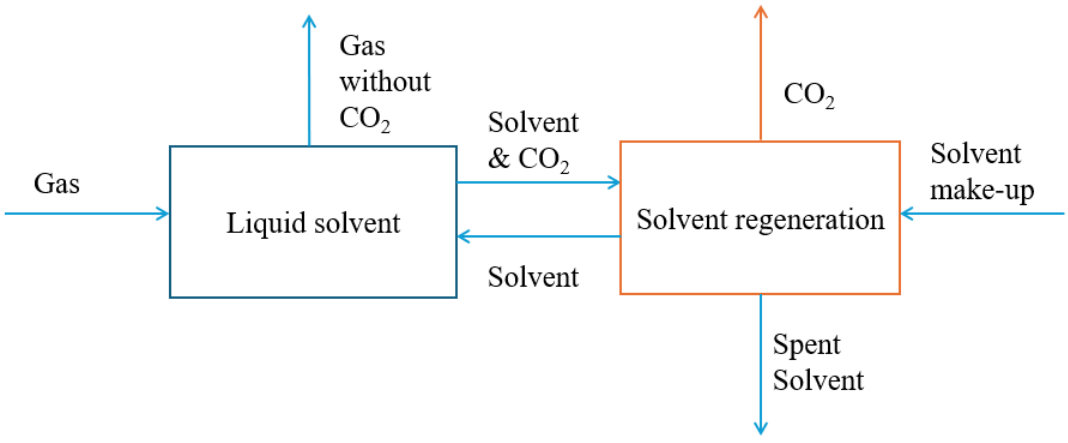

Figure 9. Absorption (Modified from CO_2 Capture Project 2008)

In the absorption technique, flue gas and liquid solvent are led to the absorption column where CO_2 absorbs into the solvent and starts to flow downwards with the solvent. Flue gas continues upwards towards the stack without CO_2. (CO_2 Capture Project 2008)

The CO_2-rich solvent is then led to the regeneration column where the solvent is heated which releases the CO_2 as a gas from the solvent. After that, the CO_2 goes upwards to be captured and the remaining solvent is cooled down and returned to the absorption column. (CO_2 Capture Project 2008)

From all the separation methods absorption is the most mature technology. (Leung et al. 2014) The technology readiness level (TRL) of absorption is 9 which means that it is commercially used in many sectors and there is a lot of research about it. It has been implemented in plants such as petroleum, cement, and power industries. If using amine-absorption the flue gas must go through denitrification and desulfurization before the absorption column. (GCCA 2025a; Vaz et al. 2022)

4.2.2 Adsorption

In adsorption, CO_2 is bound to the sorbent surface of sorbent beds under pressure under certain process conditions. The adsorbents used are selected according to the quality of the feed gas. (Vaz et al. 2022)

In adsorption, the gas is introduced under pressure into a vessel containing solid absorbent beds. These beds separate different components from the feed gas under certain process conditions such as pressure and temperature. The adsorption techniques used are pressure swing adsorption (PSA), temperature swing adsorption (TSA), and electric swing adsorption (ESA), where a change in pressure, temperature, or electricity of the process conditions results in CO_2 separation. The most common of these, PSA, is presented below. (Leing et al. 2014; Smagina 2020)

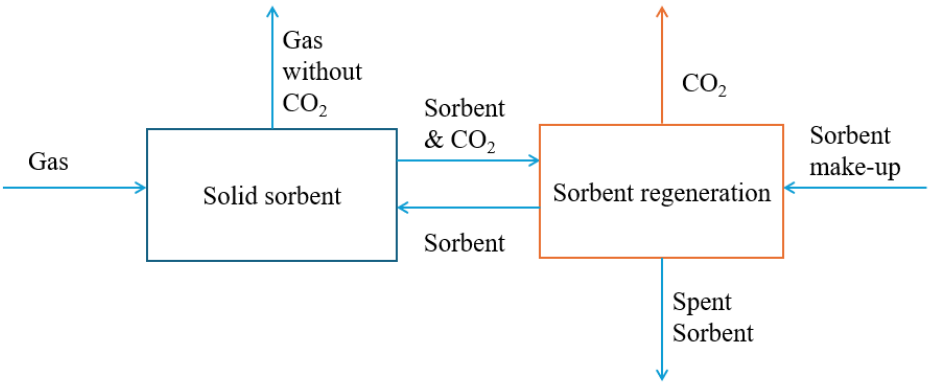

Figure 10. Adsorption (Modified from CO_2 Capture Project 2008)

In a PSA system, CO_2 is separated by creating the right pressure conditions for the feed gas as it enters the vessel, causing the adsorbent to bind CO_2 to its surface. Other, unreacted, gas components are allowed to pass through the adsorbent and out of the top of the vessel. The flow is then stopped and the pressure in the vessel is reduced, causing CO_2 to escape from the adsorbent and pass through the bottom of the vessel as gaseous pure CO_2. (Harun 2012)

The TRL of adsorption is 9, so it has been implemented commercially mainly in ethanol and natural gas processes, but it is not yet very attractive for CO_2 separation in flue gases as the capacities are quite different and there are many impurities in the gas for the sorbents. (Vaz et al. 2022)

4.2.3 Cryogenic Distillation

In cryogenic distillation, the gas is cooled and condensed so different evaporation temperatures are exploited. It is widely used for gas streams containing large amounts of CO_2. It requires quite a lot of energy, so it is not viable for streams with low CO_2 concentrations, such as combustion. Another problem is the water in the gas, which needs to be removed before cooling. The cryogenic distillation would be well-suited for pre-combustion and oxyfuel combustion capture. The advantage is ready pressurized and liquid CO_2 conditions, making transportation easier. (CO_2 Capture Project 2008)

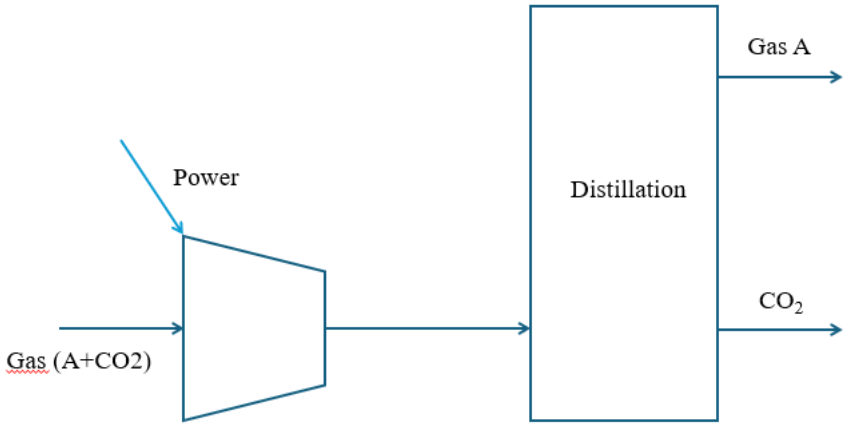

Figure 11. Cryogenic Distillation (Modified from CO_2 Capture Project 2008)

In cryogenic distillation, the gas is first pressured by external energy, and then rapidly cooled to a very low temperature, so low that the CO_2 liquefies. The gaseous components continue further in the process and the liquid components are removed from the process. The CO_2 is in liquid form and is ready to be transported.

The technology is a mature product, but CO_2 is only used at a laboratory scale. (CO_2 Capture Project 2008; IEA 2020)

4.2.4 Membrane Separation

Membrane separation is based on a membrane technique where the membrane is selected according to the molecular size of CO_2. Only CO_2 molecules pass through this semi-permeable membrane, other feed gas components continue to flow in the process, and CO_2 is removed from the process. In membrane separation, the feed gas must be cleaned and dried before the membranes, because sulfur compounds and other contaminants can damage and clog the membranes (Leung et al. 2014)

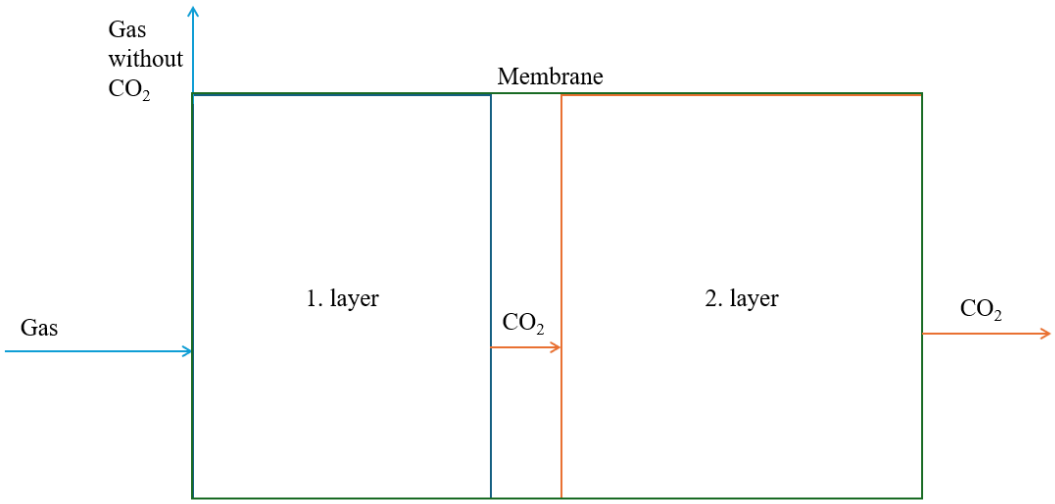

Figure 12. Membrane Separation. (Modified from CO_2 Capture Project 2008)

The TRL of membrane separation is between 6 and 7. Membrane separation is a relatively new separation method. Membrane separation is already used in natural gas streams to remove CO_2. The problem with membrane separation is the bad separation efficiency, so they must be installed in several steps of the process with different characteristics. (Harun 2012; Vaz et al. 2022)

Currently, solvent membrane combinations are being developed to achieve better properties, but they are still far from being suitable for use in flue gases. (CO_2 Capture Project 2008)

4.2.5 Gas Hydrates

Gas hydrate separation is similar to absorption, but the CO_2 is separated from the gas by water to form hydrates. The water molecules form a cage frame, and the CO_2 occupies the cage, which is called hydrate. CO_2 is collected in a dissociation reactor where the temperature is raised. This makes the water and CO_2 separate from each other. (Leung et al. 2014; Pei et al. 2024)

The problem is that the CO_2 separated is dirtier, meaning that much more of the other substances are dissolved in the water. A lot of research is currently underway into the gas

hydrate separation method. It saves a lot of energy, and the hydrate is easier to regenerate. The cons are that it needs clean gas and must be specific to work. (Leung et al. 2014)

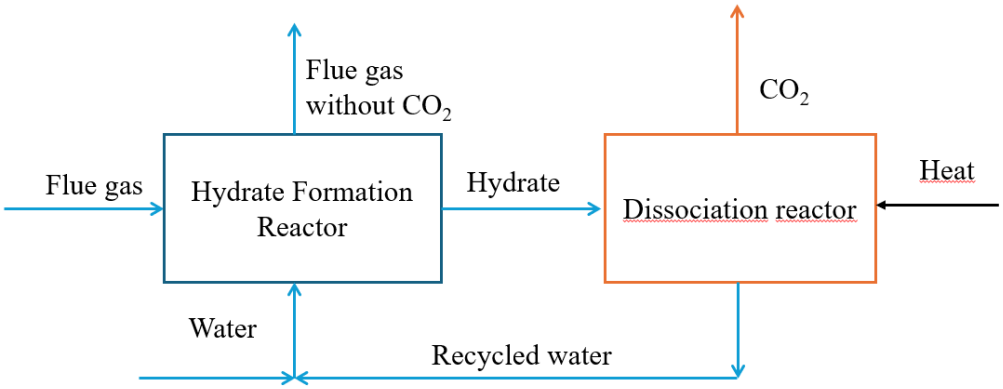

Figure 13. Gas Hydrates Separation. (Modified from Dashti et al. 2015)

4.2.6 Chemical Looping (Calcium Looping)

Chemical looping has largely evolved towards crystalline sorbents, especially in post-combustion capture, and in recent times, calcium-based substances have attracted particular interest. Calcium-based absorbents are referred to as calcium looping, which allows the separation of CO_2 from a wide variety of flue gases, in addition, the by-products can be used in the cement and lime industry. (Leung et al. 2014)

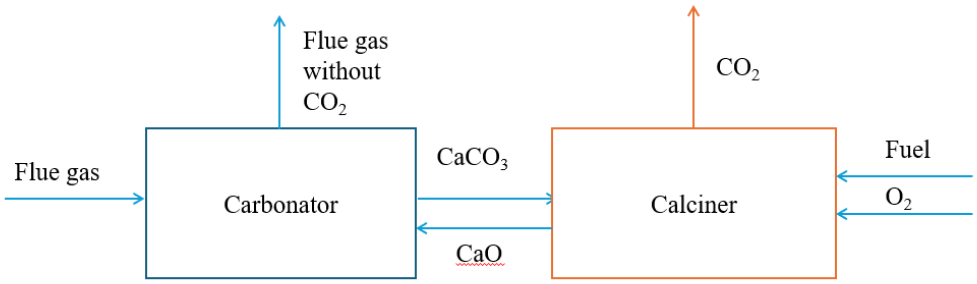

Figure 14. Calcium Looping. (Modified from Haaf et al. 2020)

Calcium looping is a chemical looping process. The process consists of two reactions that are the reverse reactions of each other, carbonation and calcination. This technique separates CO_2 from flue gases with the help of calcium oxide CaO. The reactions happen in two circulation bed units. First, the flue gas and CaO meet in the fluidized bed, where the CO_2 in the flue gas reacts with the CaO to form calcium carbonate CaCO3. The flue gas continues into the atmosphere without CO_2. (Sumitomo 2019a; GCCA 2025b)

$$CO_2 + CaO \leftrightarrow CaCO_3 \quad (4)$$

After this, the $CaCO_3$ is led to an oxyfuel calciner, where $CaCO_3$ is regenerated back to solid CaO and a gas stream of pure CO_2. (Sumitomo 2019a; GCCA 2025b)

$$CaCO_3 \leftrightarrow CO_2 + CaO \quad (5)$$

The CO_2 is removed from the process and purified. After purification, it is dried and suitable for utilization or storage. This method can be used also in cement plants. (Sumitomo 2019a; GCCA 2025b)

The TRL of calcium is 7. It is an emerging technology, and it is close to commercial large-scale processes. But it has certain difficulties, it's very energy-intensive, and it requires temperatures of 650-700 ℃ and calcination above 900 ℃. (IEA 2020)

4.3 Post-combustion Capture with Absorption

In this chapter amine and HPC absorption in post-combustion will be examined in detail. The most used carbon capture technology is post-combustion with absorption using amine water solution as an absorber. It is easiest to implement into the existing process plant, especially in coal power plants, where normally the $DeNO_x$ and desulfurization systems are already implemented. (EPCM 2023; Leung et al. 2014)

Possible amine solvents are monoethanolamine (MEA), triethylamine (TEA), and diethanolamine (DEA). MEA is the most common amine solvent. The amine solution can absorb carbon dioxide at higher or lower temperatures and release it when the pressure is reduced, or the solution is heated. In addition to meeting absorption efficiency and energy requirements, amine solutions have good resistance to repeated absorption/regeneration cycles without degradation and are non-hazardous. In MEA absorption, the flue gases must go through denitrification and desulfurization. (EPCM 2023; Leung et al. 2014)

The flue gas needs to be cooled to achieve the right temperature for the recovery reactions, so they are fed into a pH-controlled direct contact cooler (DCC). In addition, the DCC removes the last of the sulfur dioxide to avoid unnecessary amine consumption and if necessary, the DCC can be fitted with a particle module to remove fine particles. (EPCM 2023; Linde n.d.)

After DCC, the flue gas is pressurized, with a blower to overcome the absorption column pressure difference. The blower is also used to reduce the pressure drop in the absorption column, i.e., to blow the flue gas into the absorption column above its base. The bottom section acts as a buffer tank for the enriched solvent, keeping the enriched amine solvent at a suitable surface to balance the process. (EPCM 2023)

In the absorption column, the flue gas is led upwards to meet the lean amine solvent from the regeneration column. The amine solvent is injected from nozzle-mounted spray levels upstream of the flue gas. The nozzles inject the amine solvent evenly across the scrubber to ensure a large contact area between the flue gas and the amine solvent. (EPCM 2023)

The amine solvent falls from the injectors onto beds at different levels, forcing the flue gas through the bed and into contact with the amine solvent. This ensures good direct contact between the flue gas and the amine solvent and CO_2 is absorbed into the amine solvent. Since

amine absorption generates heat, making it an exothermic reaction, a self-cooling cycle between the beds is required to improve the efficiency of the process. The absorption of CO_2 with MEA. (EPCM 2023)

$$2\,R-NH_2 + CO_2 \rightarrow R-NH_3^+ + R-NH-COO^- \qquad (6)$$

The flue gas continues its upward journey through the beds and is released to the atmosphere from the top of the column, typically having stripped 90-95 % CO_2. The demisters at the top of the column separate any amine solvent in the flu gas and return it to the bottom buffer tank. (EPCM 2023)

After the amine solvent and the CO_2 absorbed by it have passed through the bed, it falls into the rich solvent and buffer tank at the bottom of the column. From the tank, the CO_2-rich amine solvent is passed through preheaters to the top of the regeneration column. In the column, the rich solvent flows downstream and meets the upstream vaporized solvent, which is vaporized by the process steam cycle. This causes CO_2 to be stripped from the amine solvent. Regeneration reaction. (EPCM 2023)

$$R-NH-COO^- + R-NH_3^+ + (Heat) \rightarrow CO_2 + 2\,R-NH_2 \qquad (7)$$

The CO_2 continues to the top of the column and from there to the condenser for cooling, where the condensate and CO_2 gas are separated and the condensate is fed back to the regeneration column, and CO_2 is then fed to further processing, pressurization, etc. The lean regenerated amine solvent falls to the bottom of the regeneration column and is pumped back to the absorption column from there through the coolers. The amine regeneration reaction is an endothermic, heat-trapping reaction, and its efficiency can be improved by heating the solvent between the beds. Figure 15 shows a typical amine separation process. (EPCM 2023)

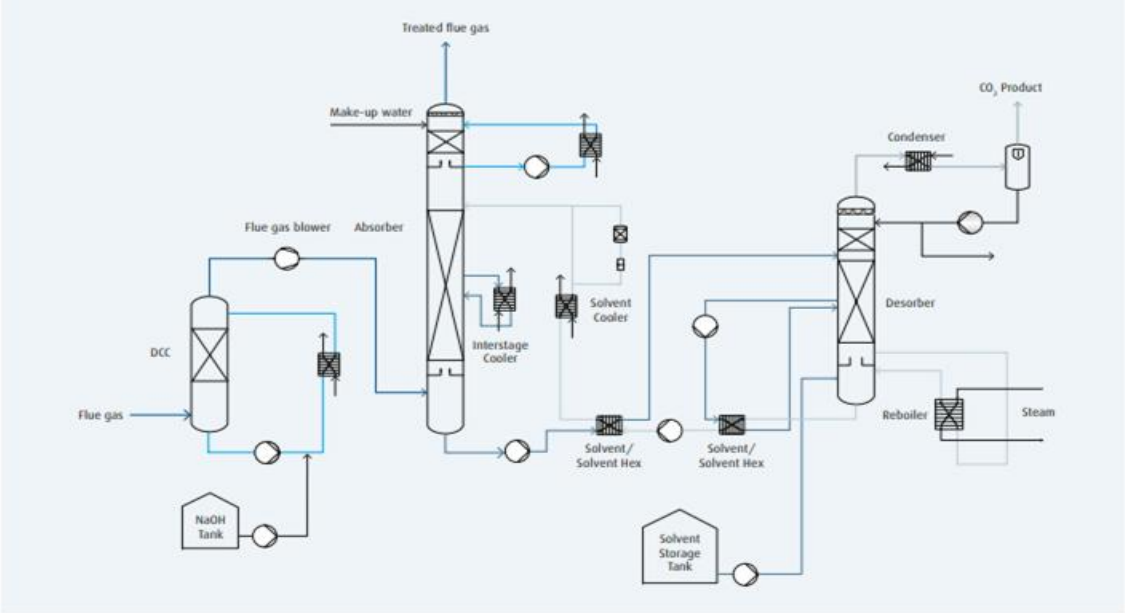

Figure 15. Amine Absorption Separation. (Linde n.d.)

Another solvent used in absorption is hot potassium carbonate (HPC). It works the same way as amine solvents, but the process does not need all the same equipment. HPC and flue gas react in an absorber scrubber, where the hot potassium carbonate binds the CO_2 in the flue gas to form potassium bicarbonate. The potassium bicarbonate is regenerated in a distillation column. The reaction with hot potassium carbonate is shown below. The regeneration is the same but in reverse. (Sumitomo 2019b)

$$K_2CO_3 + CO_2 + H_2O \leftrightarrow 2\,KHCO_3 \qquad (8)$$

Figure 16 shows the typical HPC adsorption process. It is shown to better understand how amine and HPC absorptions differ.

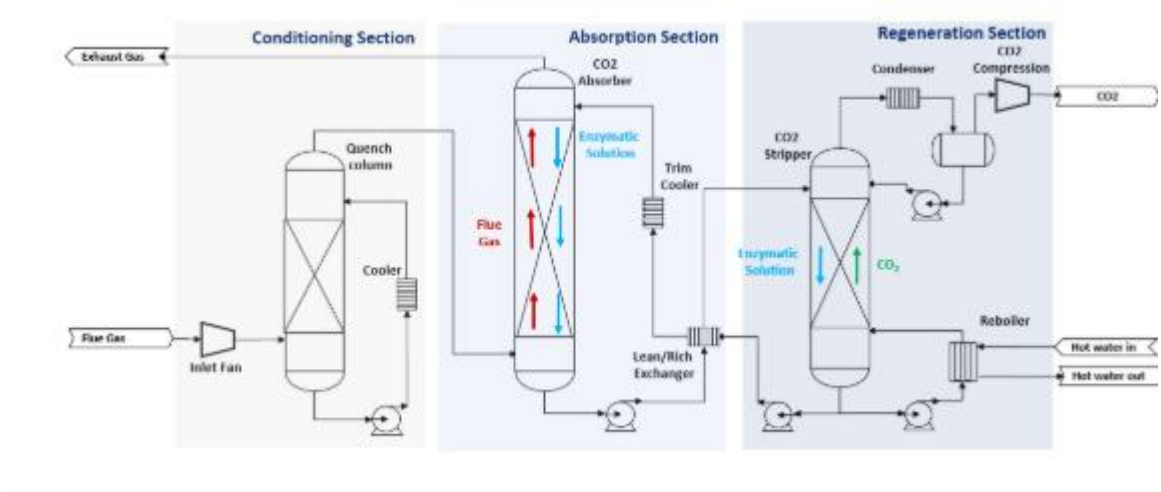

Figure 16. HPC Absorption (ACCSESS n.d.a)

Figure 16 shows the general idea of absorption as it shows the basic idea of absorption.

4.4 Comparison of Carbon Capture Technologies

Although the separation techniques are almost the same in every CO_2 capture technology Figure 8, the technologies differ greatly. Post-combustion capture uses air for combustion, while oxyfuel uses almost pure oxygen for combustion. Pre-combustion can use oxygen or air to produce CO_2. (Nanda et al. 2016)

Due to different technologies, fuels, and processes, the feed gases contain different compounds. Pre-combustion and post-combustion technologies feed gases, syngas, or flue gas, often contain NO_x, COS, SO_x, N_2, O_2, H_2, H_2S, CH_4, H_2O, and particle matter. Oxyfuel combustion also produces these, but the use of oxygen in combustion reduces the amount of nitrogen in the flue gas. Some of these compounds need to be removed from the flue gas before the CO_2 separation to avoid interference with the separation process. Sulfur and nitrogen compounds and particles must be removed from all the technologies, but SO_x and NO_x being most troublesome in post-combustion. (Nanda et al. 2016; Teir et al. 2009)

The CO_2 content of the feed gas varies widely and influences the choice of capture technology. Post-combustion technology works in the lowest CO_2 concentration range, at 4-14 %, pre-combustion's CO_2 concentration is normally 15-40 %, and oxy-fuel combustion

has the highest CO_2 concentration range, at 75-80 %. (Nanda et al. 2016; Finnish Meteorological Institute 2024b)

The capture is somehow similar for all technologies. Pre-combustion and post-combustion have a capture rate of 85-90 %. Oxyfuel has the best capture rate as it can capture up to 90-100 %. (EDF 2022)

All capture technologies also need devices/equipment to clean the feed gas to make CO_2 capture work efficiently. The size of these required devices/equipment varies considerably depending on the technology. Post-combustion needs the largest equipment, as the concentrations in the feed gas are the lowest therefore the volumes of other gas treated are the largest. Pre-combustion requires medium-sized equipment and oxyfuel requires the smallest equipment. (Nanda et al. 2016)

Post-combustion capture is the most mature of these techniques because it is the one that has been researched the most and has been used for the longest time. It has the advantage of being easier to integrate into existing plants and processes. Pre-combustion and oxy-fuel combustion capture require more modifications to existing plants and processes and therefore they are more suitable for new processes. Overall, the TRL of pre-combustion capture and post-combustion capture is 9, and for oxy-fuel combustion capture, it is level 7. This means that both pre- and post-combustion captures are commercially available and have been deployed to full scale. For oxy-fuel combustion capture, there are demonstration plants and research about it has been carried out, but it is not commercially available yet. (Bukas & Asif 2024)

In pre-combustion capture gasification, the fuel is gasified at high pressure and low temperature, and the gases go through a water-gas shift, resulting in a high CO_2 content in the feed gas for separation. The high pressure and high CO_2 content of pre-combustion technology makes capture efficiency high and because the pressure also makes the separation techniques more efficient, smaller capture units can be used. Thus, the investment cost has the potential to be lower than other technologies. However the feed gas needs to be dried and processed before CO_2 can be captured, so its capital and operating costs are high. (NETL n.d.b; Khalid et al 2022)

Post-combustion capture’s main advantage is its applicability to existing plants, as its installation requires the smallest modifications to the existing process, where removing other

compounds from the feed gas might already be taken care of. Another advantage of post-combustion capture is its use for low CO_2 concentrations. Then of course the challenge is the low CO_2 content of the gases, which makes the equipment large and the investment cost high. In addition, due to the high flow rates, it has high energy and chemical regeneration costs. (Khalid et al. 2022; Nanda et al. 2016)

Oxyfuel combustion capture has a high CO_2 content in feed gas, so it achieves higher capture efficiency than other technologies and does not require denitrification techniques for combustion. Oxy-fuel combustion capture has high operating and investment costs, as oxygen production from the air stream is expensive and energy-intensive, and the separation of oxygen from the air is done cryogenically. (Leung et al. 2014)

These differences in CO_2 capture technologies mean that different industries and different processes will choose their technology slightly differently. Many factors influence the choice of technologies, but the technologies have typical characteristics that make them more suitable for specific purposes. (DXP 2022)

Pre-combustion is often used in integrated gasification combined cycle (IGCC) power plants, as they already have a combined cycle and simply change the gas turbine to burn hydrogen. Pre-combustion is also used in hydrogen production, as it produces syngas containing CO_2 and H_2, and after CO_2 recovery hydrogen can be captured. (DXP 2022)

Post-combustion is the easiest to build to existing combustion process plants. Large combustion plants already have restrictions on their environmental permits and other gaseous substances have already been taken care of, so post-combustion is suitable for them with relatively minor process modifications. (DXP 2022)

Oxyfuel combustion is suitable for many processes but requires oxygen separation from the air. In this case, it is advantageous if nitrogen is needed somewhere near, for example, so that the plant can sell nitrogen. An oxyfuel combustion capture is therefore a good option for large industrial sites in the oil refining, cement, lime industries, and steel industries according to their needs. Of course, some modifications to the process are required, so it is more suitable for newer plants. (Cuéllar & Adisa Azapagic 2017; Khalid et al. 2022)

Table 1. Differences Between Technologies

Parameter	Pre-combustion	Post-combustion	Oxyfuel combustion
Combustion	Air or oxygen	Air	Pure oxygen
CO2 concentration	15–40 %	4–14 %	75–80 %
CO2 capture rate	85–90 %	85–90 %	90–100 %
Equipment	Middle equipment	Largest equipment	Smallest equipment
Pre-treatment	DeNOx, DeSOx, particle removal	DeNOx, DeSOx, particle removal	DeSOx, particle removal
Pros	Capture efficiencies are high Investment costs can be smaller, due to high pressure and high CO2 content	It can be implemented into existing plants Can capture small concentrations of CO2	Higher capture efficiencies No need for DeNOx
Cons	High capital and operating costs	Large equipment sizes High investment, energy, and chemical regeneration costs	High investment and operating costs
Technology readiness level	9. Commercially available and deployed to full-scale	9. Commercially available and deployed to full-scale	7. Not commercially available, pilot projects demonstrated

4.5 Storage and Utilization

After carbon dioxide has been captured, the CO_2 can be stored, permanently or temporarily, or utilized through various processes. If stored, carbon dioxide must be first pressurized and transported to a storage site by ship, pipeline, or truck depending on the distances and volumes transported. Storage options include sequestration in geological, oceanic, and terrestrial systems using specific technologies. (Ahmadian et al. 2024; Rackley 2017)

Of these, geological sequestration can be used for so-called permanent storage. It involves binding CO_2 to geological formations, empty cavities from which gas and oil or water/aquifers (not containing drinking water). Of the storage options, geological sequestration is already in commercial use. One geological storage is enhanced oil recovery (EOR), where CO_2 is injected into oil reservoirs. Carbon dioxide cannot be stored in Finland, so it must be transported to the nearest storage site in the North Sea, the Norwegian Sea, or the southern Baltic Sea. Transportation costs a lot, by pipeline or truck/ship, because the

quantities are large and the transport chain would have to include short-term storage, which costs even more. (Rackley 2017; Finnish Government 2023)

The so-called cyclic storage can be used in ocean sequestration, which pumps carbon dioxide to the bottom of the ocean. From there it is gradually released back into the atmosphere. Another option is terrestrial ecosystems, which are based on biochemical processes, the natural cycle of carbon dioxide, and its control. In it, carbon dioxide is stored in plants and thus in the soil, through photosynthesis. However, both options are only small-scale storage and are not therefore very good alternatives, nor do they remove carbon dioxide from the atmosphere in the long term. (Rackley 2017; Finnish Meteorological Institute 2024b)

In addition, carbon can be stored in minerals. During mineralization, CO_2 reacts with minerals forming various compounds, carbonates, and silicones. The reaction can take place in nature or industrial processes and the product can be stored for CO_2 for a long time. (Rackley 2017; Finnish Meteorological Institute 2024b)

In utilization, CO_2 is used as a raw material to produce value-added products. There are currently three ways in which CO_2 can be utilized: mineralization, chemical, and biological conversion. Mineralization also produces products that can act as both storage and utilization. In chemical conversion, CO_2 can be used to produce polymers, fuels, chemicals, beverages, and food through chemical processes, while in biological conversion, CO_2 is converted by microorganisms into useful products such as chemicals and plastics. (Ahmadian et al. 2024)

There are many uses for CO_2, and CO_2 capture could also be used for this purpose. Carbon dioxide is used in the food and beverage industry, to extinguish fires (in fire extinguishers), refrigeration, water treatment, as a shielding gas in welding, and in stimulating biological growth. (IEA 2019)

In addition, many new uses for carbon dioxide have been developed, such as manufacturing concrete and plastics. However, the greatest potential for the use of carbon dioxide lies in synthetic fuels, which usually combine carbon dioxide and hydrogen, due to their high volumes. (IEA 2019)

Depending on the application, the purity of CO_2 is required to be cleaner in the food and beverage industry than in industrial processes. Table 2 shows the quality requirements for CCUS in general (NPL n.d.).

Table 2. CCUS allowed impurities (NPL n.d.)

Component	**Upper limit [µmol/mol]**	
	Minimum	Maximum
H_2O	20	50
H_2S	5	20
O_2	10	20
CH_4	10 000	40 000
N_2	10 000	40 000
Ar	10 000	40 000
H_2	50	20 000
C_2H_6	10 000	40 000
C_3^+	1 500	20 000
CO	100	2 000
SO_x	10	100
NO_x	10	100
NH_3	10	1 500
Particulates	1	1
HCl	10	70
HF	10	70
HCN	10	70
Glycol	0.025	0.05
MEA	0.08	1
Amine	10	10
Formaldehyde	20	60
Acetaldehyde	20	60
Cadmium	0.01	0.03
Selexol	0.6	0.6

To store carbon dioxide the CO_2 purity must be 95 %. The CO_2 purity required for utilization depends largely on the application. Medicine, food, and beverage industries need a CO_2 purity of more than 99 %. CO_2-enhanced oil recovery needs the CO_2 purity to be around 96 %. Depending on the industrial process, the CO_2 purity can vary widely between 80-99 %. Although CO_2 purity does not always need to be so high, it poses a challenge for carbon capture, as it costs too much to achieve those purity values. Therefore, the carbon capture technologies can be seen as a more important challenge than the storage and utilization techniques. (Finnish Meteorological Institute 2024b; Thunder Said Energy n.d.)

5 Current Carbon Capture Projects

The interest in carbon capture has increased in Europe in recent years with the new targets to limit climate change, although carbon capture has been in the picture for a longer time. Carbon capture started in the 1960s in oil recovery at CO_2-enhanced oil recovery. The modern idea of carbon capture was born in 1996 and the first project followed soon after. The importance of CCS was more widely recognized after the 2005 IPCC Special Report on Carbon Capture and Storage. (Ma et al. 2021; IEA 2016)

In 2023, there were around 395 commercial CCS projects, 190 in early development, and 43 in operation. Most of the projects are in North America. In Europe, Norway, Denmark, the Netherlands, and the UK are leading the way in carbon capture projects and there are now 119 commercial-scale projects. (Statista 2024b; Levina et al. 2023)

Table 3. European Projects (ZEP n.d.)

Project name	**Location**	**Project category**	**Start year**	**Capture rate [t/y]**	**Reference**
Hafslund Oslo Celsio	Norway	CCS in energy production	2026	400 000	CEWEB n.d.
Norcem	Norway	CCS in industry	2025	400 000	Heidelberg Materials n.d.a
Project Greensand	Denmark	CO_2 transport and storage	2025	1 500 000	Global CCS Institute 2023
C4 - Carbon capture Cluster Copenhagen	Denmark	CCS in energy production	-	3 000 000	Carbon Capture Cluster Copenhagen n.d.
Flite	Belgium	Carbon capture and Utilisation	2025	-	Flite n.d.
H-Vision	Netherlands	Low-carbon hydrogen production	2027	1 300 000	H-vision n.d.
CinfraCap	Sweden	CO_2 transport and storage	-	2 000 000	WSPS n.d.
Net-Zero Teesside	UK	Full-chain CCUS project	2027	2 000 000	Net Zero Teesside
ECO2CEE	Poland	CO_2 transport and storage	2027	1 000 000	HOLCIM n.d.
CarbFix Project	Iceland	CCS in energy production	2025	25 000	European Commission n.d.d
ViennaGreenCO_2	Austria	Test centre	2018	-	Energy innovation Austria n.d.
La Robla Green	Spain	CC in energy production	2026	164 000	La Robla Green n.d.

Many European governments are supporting carbon capture by developing sustainable roadmaps and strategies and including carbon capture in them. Denmark for example, has committed to becoming a European CCS hub and the government in Denmark is supporting CCS implementation subsidies. Table 3 shows some of the European projects. (Levina et al. 2023; ZEP n.d.)

Finland has a Sustainable Growth Programme to finance €150 million for carbon and hydrogen utilization and capture projects. There are not yet large-scale commercial carbon capture plants in Finland however there is a lot of research done about it right now. From Table 4 some of the Finnish projects are shown. (Levina et al. 2023)

Table 4. Finnish Projects

Project name	**Location**	**Project category**	**Start year**	**Capture rate [t/y]**	**Source**
Q Power	Tampere	CCU, power-to-gas	-	-	Kujanpää et al. 2023
Q Power	Kerava	CCU, power-to-gas	-	16 500	Kujanpää et al. 2023
Carbofez	Nokia	Biochar, pyrolysis	-	7000	Kujanpää et al. 2023
Joensuu Biocal Oy	Joensuu	Biomass torrefaction to biocoal	-	60 000	Kujanpää et al. 2023
Ren-gas	Pori	CCU, power-to-gas	2028	300 000	REN-GAS n.d.
Ren-gas	Kerava	CCU, power-to-gas	2027	37 000	REN-GAS n.d.
Ren-gas	Tampere	CCU, power-to-gas	2027	110 000	REN-GAS n.d.
Ren-gas	Lahti	CCU, power-to-gas	2027	70 000	REN-GAS n.d.
Ren-gas	Kotka	CCU, power-to-gas	2027	110 000	REN-GAS n.d.
Ren-gas	Mikkeli	CCU, power-to-gas	2027	37 000	REN-GAS n.d.
Fortum	Riihimäki	CCU, plastics recycling. Research phase	-	-	Kujanpää et al. 2023
Westenergy	Koivulahti	CCS, CCU	-	20 000	Kujanpää et al. 2023
Vantaan Energia	Vantaa	Power-to-gas	-	-	Kujanpää et al. 2023

6 Major Companies in the Carbon Capture Field

More and more companies are investing money in carbon capture and its development. It is therefore important to identify the key companies working with carbon capture. Many companies in the oil, power, waste-to-energy, and forest industries are searching for ways to include carbon capture in their emission reductions. A few major companies include Shell and Linde. Shell and Linde both provide their expertise and solutions to others. (Extrapolate 2022)

It is also good to identify European companies who work with carbon capture: SAIPEM, Aker Carbon Capture, and Sumitomo. Saipem is a company that provides carbon capture solutions specializing in absorption with hot potassium carbonate. Aker Carbon Capture works on carbon capture and can provide solutions for all parts of CCS. They have expertise in large-scale projects and commercializing solutions. (SAIPEM n.d.; Aker Carbon Capture 2024)

Sumitomo is working on carbon capture and storage. They have developed oxy-fuel combustion capture, as well as calcium looping and hot potassium carbonate separation technologies. (Sumitomo 2023)

In Europe, there is a consortium called ACCSESS with 18 partners in it. The consortium has knowledge and expertise across the CCUS chain. The consortium's member partners represent four industrial sectors with high potential for carbon capture: cement, forestry, biorefineries, and waste-to-energy. (ACCSESS n.d.b)

ACCSESS has, among other things, funded a pilot project for Stora Enso in Skutskär, Sweden. SAIPEM, an ACCSESS company, has also been a partner in the Stora Enso project, acting as a technology supplier. This has aimed to develop carbon capture into a cost-effective operating model and analyze what it does to the environment. (Sherrard 2024)

In addition, two other companies in the consortium, Linde and Heidelberg Materials, have joined forces to create a carbon capture and utilization plant at the Lengfurt cement plant in Germany. The captured CO_2 will be converted into a raw material for the chemical and food industries. (Heidelberg Materials n.d.b)

Existing customers, particularly large coal-fired power plant owners, could easily identify large companies potentially interested in carbon capture. Forest industry companies, the energy industry, biogenic carbon, and the cement industry are viable options for starting carbon capture in Finland. Other major emitting companies will probably wait until the price per ton of emission rises or capture technologies fall sufficiently.

In Finland, Fortum Recycling and Waste has successfully captured CO_2 from the flue gases of its Riihimäki waste incinerator. It is called the Carbon2x pilot program, wherein the first stage, captured CO_2 was combined with hydrogen to produce e-methane. In autumn 2023, the second phase of the pilot was able to produce biodegradable plastic from the carbon dioxide from waste incineration (CCU). (Fortum n.d.)

Q Power has also carried out pilot projects for carbon capture plants in Finland at Keravan Energia. In Finland, industrial-scale carbon capture plants are currently in operation in Harjavalta, P2X, and Q Power, which produce e-fuels (e-methane). (Kujanpää et al. 2023b)

Other carbon capture projects are in the feasibility phase but do not yet have investment decisions, for example, the Vantaan Energia CCS study. Project suppliers operating in Finland include Ren-Gas and ST1. (Kujanpää et al. 2023b)

In Finland, there are engineering/technology suppliers: Ren-Gas, LUT/VTT, Horisont Energy, AFRY, Elomatic, and WOIMA. In addition, there are many companies in the equipment market, possibly even the same as for FGD plants. (Kujanpää et al. 2023b)

7 Materials and Methods

In this chapter, the methodologies of market study and case study are shown. There are still few carbon capture projects in the world and only a few in Finland. This makes it difficult to find and verify financial information, but some costs for plants and their operation have been calculated using source data to find the right magnitude.

7.1 Market Study Methodology

Market research is the first step in identifying new services and products and their markets before making major strategic decisions and taking concrete action. The market study starts by identifying new markets, market areas, sectors, and business opportunities. The aim is to identify industries and the related processes for which the company has existing knowledge, contacts, technology, and commodities that the company could apply in the new market. (Lehtonen 2004)

The sources used are scientific reports and reports published by international and governmental organizations. The impact of incentives and regulations on the market was analyzed through scientific reports, legislation, and international agreements published by Finland and the EU. Market forecasts and growth figures were analyzed using research reports on carbon capture published by the EU and Finland. Customer interest in carbon capture has been collected through various company reports and a customer survey.

It isn't easy to see the current potential and size of the domestic market, as all projections depend heavily on political decisions. For this reason, a customer survey was sent to the largest companies in the largest industries based on emissions trading. The industries were forest, energy, steel, chemical, and mineral. A total of 16 companies were contacted with 7 responses. No responses were received from the forest industry, the other sectors are represented. The questions can be found in Annex 1.

7.2 Case Study Methodology

The cost of carbon capture varies widely depending on, among other things, the application, the carbon capture technology and separation technique, the purity, and its operating environment. In addition, the chosen boundaries of the carbon capture affect the costs. In this study, the costs are calculated for carbon capture, compression and liquefaction, and intermediate storage.

Currently, the most expensive part of the capture process is the capture itself, as the separation and compression of the CO_2 consumes a lot of energy. It has been found that CO_2 capture reduces the power plant's electricity production by an amount equal to the efficiency loss by about 7-13 %, in some cases even more. About half of the investment costs come from the actual capture system and the rest comes from the CO_2 treatment. Since the costs of further processing of carbon dioxide are not widely available for plants of different sizes, it has been assumed that these costs will increase in the same proportion as the cost impact of plant size on the price of CC. (Teir et al. 2009)

Carbon dioxide capture can be retrofitted to existing combustion plants or when new plants are built. The expected remaining lifetime of an existing plant plays a major role in constructing a capture system. (Kujanpää et al. 2023a)

A cost analysis for carbon capture estimates the costs of adding a carbon capture facility to an existing plant that burns biomass (wood). The calculations use post-combustion capture with amine absorption and hot potassium carbonate absorption and compression into a storage tank. The costs of these capture processes are determined by two different power plants, 200 MW_f and 400 MW_f. The costs of amine absorption capture are compared with the costs of HPC to see the differences between different separation techniques.

The first step of the calculation is to determine the flue gas flow and CO_2 emissions of the power plant to calculate the actual size of the carbon capture plants and hence real cost.

The calculation starts with the mass flow of CO_2 emissions. The calculation is done using equation 9:

$$q_m = P_f * j \tag{9}$$

Where q_m on the mass flow of CO_2 [kg/s], P_f on fuel input (fuel power) [MW_f], ja j is the CO_2 emission coefficient of wood [t_{CO2}/GJ].

When the mass flow of CO_2 is calculated, it is possible to calculate the amount of CO_2 emissions per year. It can be calculated using the equation:

$$m = q_m * t_h \quad (10)$$

Where m is the amount of CO_2 emissions per year [t/a] t_h is peak operating time [h/a]. Peak operating time refers to a time during which a year's energy output would have been produced at the power plant's maximum power output. (Motiva 2024)

The annual energy input of the power plant needs to be studied as it also affects the amount of CO_2. The annual energy input is calculated using equation 11:

$$E = P_f * t_h \quad (11)$$

Where E is the annual energy input [MWh/a], P_f on fuel power [MWf], and t_h is the peak operating time [h/a]

The flue gas flow rate is calculated next. The flue gas flow rate is calculated because it indicates how much gas the capture unit should be able to handle.

$$V = P_f * \mathrm{j} \quad (12)$$

Where V is the flue gas flow rate [Nm^3/s] and j is the emission coefficient of wood [Nm^3/MW]. The mass flow q_m of the flue gas can be calculated with equation 9, where j_n is the wood emission coefficient [kg/MW].

Now to the cost estimation. The first step is to look for general CO_2 removal efficiencies, which are typically 90 % for post-combustion processes. Equation 13 is used to calculate the potential amount of CO_2 captured. (EDF 2022)

$$m_{cc} = m * \eta \quad (13)$$

Where m_{CC} is the possible captured CO_2 amount [t/a] and η is CO_2 removal efficiency.

CAPEX, lifetime, and interest values are sought from literature sources. CAPEX refers to investment costs and is in [M€] units. (Ross 2021)

The study compares the costs between two different plants, with CAPEX calculated for the larger plant size through a scaling benefit. It is calculated using equation 14.

$$C_{CAPEX} = C_{CAPEX,ref} * (\frac{P}{P_{ref}})^{St} \quad (14)$$

Where C_{CAPEX} is the CAPEX investment [M€], $C_{CAPEX,ref}$ is the known CAPEX investment cost, P is the Power [MW] and s_t is the scale factor 0.7.

The annual CAPEX costs are calculated using the annuity payment method. Annuity means payments paid back at equal intervals to repay a loan, for example.

$$C_a = C * i/(\frac{1-1}{(1+i)^n}) \quad (15)$$

Where C_a is the annual cost per ton of CO_2 [M€/a], i is the interest rate and n is the lifetime.

OPEX refers to operating costs. In this calculation, OPEX has three variable costs: heat, electric power, and MEA. The heat, electricity, and MEA cost is calculated using equation 16. (Ross 2021)

$$C_{OPEX} = E * C_{price} * m_{cc} \quad (16)$$

Where C_{OPEX} is the annual variable OPEX cost [M€/a] E is the annual consumption in [MWh/a] or [t_{MEA}/t_{CO2}] and the C_{price} is the yearly price [€/MWh] or [€/t_{MEA}] and m_{CC} is the annual captured CO2 amount [t/a]. Variable OPEX costs are affected by how much CO_2 is produced. (Ross 2021)

Fixed OPEX refers to costs that remain the same regardless of how much CO_2 is produced. Fixed OPEX is calculated with CAPEX, and it is determined to be 6 % of CAPEX. (Beiron et al. 2022)

$$C_{Fixed\ OPEX} = \%/C_{CAPEX} * C_{CAPEX} \quad (17)$$

Where $C_{Fixed\ OPEX}$ is [M€/a] and C_{CAPEX} is [M€/a]. Now the total OPEX can be calculated with equation 18:

$$C_{total,OPEX} = C_{Fixed\ OPEX} + C_{Variable\ OPEX} \quad (18)$$

Where the $C_{total,OPEX}$ is [M€/a]. And finally, the total costs can be calculated with equation 19:

$$C_{total} = C_{total,OPEX} + C_A \quad (19)$$

The annual costs can be presented in the unit [€/t_{CO2}]

8 Results and Discussion

The market study results, and case study results are discussed in this chapter. Calculating costs is useful to keep up with the size of the facility and projects, both in financial and workload terms. There are still few carbon capture projects in the world and only a few in Finland. This makes it difficult to find and verify price data, but some costs for plants and their operation have been calculated using source data to find the right proportions.

8.1 Market Study Results

The market study familiarizes the carbon market, size, and potential. It sought to identify customer data and understand the impact of incentives and regulations in this market. As carbon capture is still in its infancy, mainly due to the high investment and operating costs of capture, it is useful to understand the market. The market was studied globally, but due to the sheer volume of data and the difficulty of verifying its accuracy, it was decided to focus on Finnish emissions data for different sectors. The bio-based carbon capture was mainly studied in Finland, as the forest industry and combustion in industrial processes in Finland create a large potential for carbon capture in bioenergy. (Kujanpää et al. 2023b)

A functioning market is a crucial element for the development of carbon capture. A product or service will not sell to customers without a functioning market. It is important to consider the factors that influence the development of the market, such as the objectives and regulations in each region. However, the market must operate and develop following these international agreements. Of course, this diversity means some can produce products at lower “environmental” costs than others. For example, guidelines and legislation created by the EU have an impact on the EU market, as do the EU countries’ own local rules. (EEA 2022)

The global market for carbon capture is still relatively small, but its potential to combat climate change is still seen as high, so the market for carbon capture is expected to grow. In 2023, the global CCS market was 2 billion USD and is forecast to grow to 7 billion USD by 2031. The market for CCU was 4 billion USD and is forecasted to grow to 11 billion USD (Statista 2024a; Zion market research 2024)

Regionally, North America is projected to dominate the carbon capture market due to the high level of investment in research and development and the many high-capacity CO_2 capture plants already in operation. Europe is expected to be the second largest market for CO_2 capture as CO_2 capture solutions are increasingly used in Europe for various commercial applications. (Extrapolate 2022)

Industrialization, production growth, and various legislative measures to reduce greenhouse gases are expected to increase the need for carbon capture. In addition, the growing energy demand will increase the need for carbon capture markets, as will society's growing concern about carbon emissions. (Extrapolate 2022)

The main challenges for the growth of carbon capture are seen in the high investment costs of CCS and the significantly lower prices of crude oil, which reduces the demand for CO_2-based applications and synthetic fuels. These are expected to be countered by various support solutions by governments to increase economic activity in terms of employment in the market (green transition) and decarbonization, which would significantly stabilize the market. (Extrapolate 2022)

Now, it seems that the investment and operating costs of carbon capture still drive up the captured CO_2 price too high. This means that the commercial market itself does not yet generate significant investment in carbon capture. It is, therefore, worth exploring the future of the carbon market a little.

Now, it seems that the costs for CCUS still push CO_2 prices too high, so the commercial market is not yet driving investment in CCS to any significant extent. However, there is already an existing market for carbon dioxide, where it is traded in emissions trading, in the merchant market, and in the captive market. In emissions trading, a price per ton of CO_2 emitted is set according to the needs as operators buy emission permits. In the merchant market carbon dioxide is traded as a raw material for products while in the captive market, it is used as a raw material in companies' processes. (Kiviranta & Linjala n.d.)

Global carbon dioxide consumption is 230 megatons per year, worth around 7.8 billion USD (€ 7.48 billion). Carbon dioxide consumption is expected to grow steadily over the coming years to 272 megatons in 2025. The largest consumer of carbon dioxide is the fertilizer industry, followed by the oil and gas industries. The main markets for carbon dioxide are North America (33%), China (21%), and Europe (16 %). The demand for carbon dioxide in

Europe for example is about 36.8 megatons. New uses for carbon dioxide will also create new markets for both carbon dioxide and carbon capture. (Kujanpää et al. 2023b; Kiviranta & Linjala n.d.)

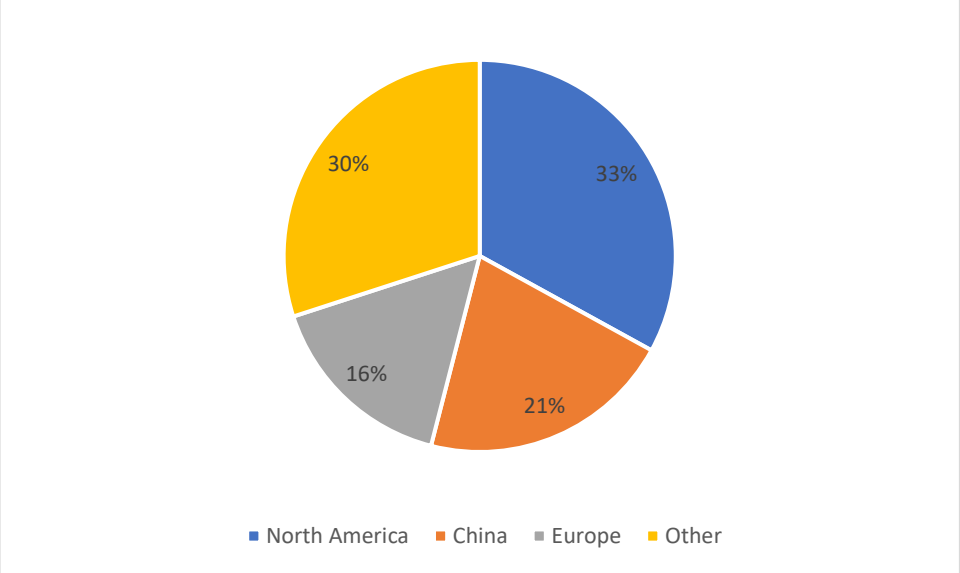

Figure 17. Global CO_2 Consumption (Kiviranta & Linjala n.d.)

The demand for the consumption of CCU products is expected to grow by more than 1000 USD billion by 2050, with the development of synthetic fuels as a major variable. (Mäkikouri et al. 2024)

In 2021, industrial production of carbon dioxide in Finland was around 225 kt of which around 190 was sold. The total sales value was €19.9 million, giving an average estimated price for carbon dioxide of 105 €/t_{CO2}. (Kiviranta & Linjala n.d.)

The greater market potential for carbon dioxide lies in emissions trading systems, currently covering the energy, industry, and transport sectors, aiming to reduce emissions cost-effectively. In addition to the EU ETS, other important emissions trading systems are in North America, China, South Korea, the UK, and New Zealand. (Kujanpää et al. 2023b)

In Europe, total CO_2 emissions in 2021 were 2.88 gigatons. In 2021, the European ETS market size was €683 billion. This represents about 90 % of the value of the global carbon market. The price of carbon dioxide has increased and one reason for this is the EU's

tightening climate policy. The price of carbon emission allowance has fluctuated between 70 € and 100 €/t_{CO2} over the last few years. The allowance price is projected to stay around 70 €/t_{CO2} until around 2034, after which the price would rise to 130 €/t_{CO2}. (Kujanpää et al. 2023b; Kiviranta & Linjala n.d.)

In Finland, the emissions trading system is worth around €582 million. The largest companies in Finland covered by emissions trading in the iron and steel industries are Boliden, SSAB, Ovako, and Outokumpu. Finnsementti is a major emitter in the cement industry. In the chemical industry, the big emitters are Borealis, Taminco, and Yara. Other large industrial emitters are Neste in the oil industry, Nordkalk in the lime industry, Saint-Gobain Finland Oy in the building products industry, and Paroc Ab oy in the stone wool insulation industry. Compared to the rest of the world, Finland has no aluminum industry, but the forest industry is a major player in Finland. Finland's three big forest industry companies are Stora Enso, Metsä, and UPM. In the energy sector, the big players are Helen, Fortum, Turun Seudun Energiantuotanto, Vaasa Energia, Oulu Energia, Tampereen Energia, and Vantaa Energia. Table 6 shows the 25 biggest emitter companies that are included in emissions trading. The numbers do not include the bio-based CO_2 emissions. (Energiavirasto 2024)

Table 6. Emissions Trading

Company	**2023 [tCO_2]**
SSAB Europe Oy	3 805 494
Neste Oyj	2 529 098
Helen Oy	1 632 791
Finnsementti Oy	663 883
Outokumpu Stainless Oy	632 428
Fortum Power and Heat Oy	535 556
Borealis Polymers Oy	466 839
Stora Enso Oy	418 709
UPM-Kymmene Oyj	289 462
Nordkalk Oy Ab	265 520
Metsä Group Oyj	262 504
Oy Linde Gas Ab	239 472
Oulun Energia Oy	238 725
Tornion Voima Oy	232 434
Jyväskylän Voima Oy	206 032
Tampereen Energia Oy	205 130
Vantaan Energia Oy	190 193
Turun Seudun Energiantuotanto Oy	154 833
Kuopion Energia Oy	145 608
MM Kotkamills Boards Oy	142 993
Vaasan Voima Oy	119 525
Seinäjoen Voima Oy	115 893
Savon Voima Oyj	112 715
SMA Mineral Oy	107 877
Kilpilahden Voimalaitos Oy	94 948

In 2022, CO_2 emissions from the industrial sector in Finland were about 45.3 Mt_{CO2}. Of these CO_2 emissions, about 30 Mt_{CO2} were biogenic from renewable fuels, and the rest from fossil fuels. (This only includes the facilities with more than 100 kt_{CO2}.) The forest industry was responsible for about 21.7 Mt_{CO2} of the CO_2 emissions from industry. The other major emitters were thermal power stations and combustion installations, with 15.2 Mt_{CO2}. (Mäkikouri et al. 2024)

In the forest industry, 20.4 Mt_{CO2} of the CO_2 emissions were biogenic, while in thermal power stations and combustion installations, biogenic CO_2 emissions amounted to 8.8 Mt_{CO2} and in waste-to-energy to 0.8 Mt_{CO2}. On average, bio-based industrial production is more important than in the rest of the world. The biogenic carbon capture potential in Finland is around 5-20 Mt_{CO2}/year. (Mäkikouri et al. 2024)

The large biogenic sources of CO_2 emissions from the forest industry, as well as the energy industry, allow for large-scale bio-based carbon capture. This could be well linked to the construction of technical sinks.

In Finland, BECCS is considered to play a larger role than conventional CCS. This is because capturing and storing carbon dioxide from fossil fuels does not contribute to creating technological carbon sinks. The problem with technological carbon sinks is that there are no financial incentives for them in Finland, at least not yet, and they currently do not benefit financially from support schemes. (Kujanpää et al 2023a.)

An alternative to storage is the utilization of bio-based carbon capture. Of the utilization options, bio-based synthetic fuel production has the greatest potential and is seen as a huge opportunity. Of course, there are a few obstacles to overcome before things can move in this direction. In Finland, synthetic fuel's potential is estimated at 2-3 Mt_{CO2}/year. (Mäkikouri et al. 2024)

In the chemical industry, captured CO_2 is thought to replace fossil carbon in processes and products such as oil refining, plastics, or packaging. The potential there is estimated at 2-3 Mt_{CO2}/year. There are also ideas for replacing building aggregate minerals with captured CO_2, with a potential of 0.2 Mt_{CO2}. (Mäkikouri et al. 2024)

However, these are short-lived products and cannot act as technological carbon sinks, as they quickly release carbon dioxide back into the atmosphere. Overall, it is estimated that in 2040, Finland will have already invested €11 billion in CCUs and the value of CCU products in 2040 would be €7 billion. (Kujanpää et al. 2023a; Mäkikouri et al. 2024)

Although the capture price seems to be moving towards a reasonable price, storage and utilization problems remain. At present, the market for storage and utilization is too small, which means that there is a need for intermediate storage for CO_2. This also means that the location of the capture plant must be near good transportation facilities or the end user of CO_2.

8.1.1 Customer Survey

A customer survey was conducted to identify potential customers and their interest in carbon capture. The customer survey was conducted for Finnish companies using the Survio survey tool. The survey has 10 questions related to carbon capture. Seven customer companies responded to the survey, of which two were from the energy industry, two from the steel industry, two from the chemical industry, and one from the cement industry.

All companies were familiar in some way with the concept of carbon capture. Most of the responding companies saw carbon capture as a solution to mitigate climate change and that the use and implementation of carbon capture will increase in the coming years.

Carbon capture is also seen as a potential competitive advantage and many companies' customers are interested in carbon capture. Customer interest in carbon capture has increased, as environmental awareness has grown. They are more aware of climate targets and regulations, and this has led to growing expectations of corporate responsibility. Many see carbon capture as more attractive if, once captured, it is utilized.

Most companies believe that carbon capture will increase by 2030 or 2040. However, the cost of carbon capture is seen as too high by many companies, hence the perception that it is easier to reduce emissions than to capture carbon dioxide. Carbon capture is seen as a potential source of emission reductions, but many stressed that this can only happen with the right support and funding.

Carbon capture is currently seen as too expensive. The infrastructure and other costs required are too high for many companies. There is also a problem with the lack of commercial technologies: CO_2 capture efficiency is not optimal, the technologies are energy intensive and in some situations the flue gas is too diluted, making it difficult to capture CO_2.

The customer survey results show the potential of CO_2 capture as a tool to mitigate climate change. Its deployment will require technological development, support, regulation, and cost reductions.

8.2 Case Study Results

Table 7 presents the results of the power plant calculations without carbon capture. These results are the same for amine absorption and HPC absorption. Case1 presents the 200 MW_f powerplant and Case2 presents the 400 MW_f powerplant.

Table 7. Power Plant Calculations

	Unit	**CASE1**	**CASE2**
Fuel power	MW_f	200	400
Peak hours	h/a	5 000	5 000
Fuel energy	MWh/a	1 000 000	2 000 000
Emission coefficient (OFS 2025)	kg_{CO2}/GJ	112	112
CO_2 emission (no CCS)	t/a	403 200	806 400
CO_2 removal efficiency	%	90	90
Captured CO2 amount	t/a	362 880	725 760

Prices and costs from various sources have been used in the calculation and scaled up to fit the 200 MW_f power plant. The CO_2 content of the emission source, the fuel, and the size of the plant influence the costs. Various sources have found that these have a major impact on the cost of capture.

The costs were studied by searching for CAPEX values for plants of different sizes and fuels and comparing these with the calculations. This approach was also used to estimate the cost of an additional 400 MW plant, by scaling up equation 7. The analysis shows the advantage of a larger generation volume and greater effectivity leading to lower costs.

For the OPEX costs, the fixed share of annual operating costs was estimated to be commonly used at 6 % of CAPEX (Beiron et al. 2022). Variable costs were obtained by looking at the specific electricity, heat, and amine consumption and their commodity prices from different sources, leading to Tables 8 and 9.

Table 8. CAPEX and OPEX for Amine Absorption

	CAPEX	**Unit**	**CASE1**	**CASE2**
	CAPEX	€/t	275.6	242.8
	CAPEX (Q Power& Tampereen sähkölaitos, 2023)	M€	100	134.4
	Lifetime	a	20	20
	Interest	%	5	5
	OPEX			
Variable	Heat price	€/MWh	50	50
Variable	Electric power price	€/MWh	80	80
	Heat consumption (Capsol Technologies 2025; Q Power& Tampereen sähkölaitos, 2023)	kWh/t_{CO2}	550	550
	Electric power consumption (Capsol Technologies 2025; Q Power& Tampereen sähkölaitos, 2023)	kWh/t_{CO2}	150	150
	MEA (Finnish Meteorological Institute 2024b)	kg//t_{CO2}	1.6	1.6
	MEA price (Chemicalmarket, 2023)	€/kg	1.26	1.26
Fixed	Fixed OPEX	%/CAPEX	6	6

Table 9 shows the data on HPC absorption that was found.

Table 9. CAPEX and OPEX for HPC Absorption

	CAPEX	**Unit**	**Case1**	**Case2**
	CAPEX	€/t	248	219
	CAPEX (Capsol Technologies 2025)	M€	90	121
	Lifetime		20	20
	Interest	%	5	5
	OPEX			
Variable	Heat price	€/MWh	50	50
Variable	Electric power price	€/MWh	80	80
	Heat consumption (Capsol Technologies 2025)	kWh/t_{CO2}	300	300
	Electric power consumption (Capsol Technologies 2025)	kWh/t_{CO2}	110	110
	HPC (Capsol Technologies 2025)	€/t_{CO2}	0.25	0.25
Fixed	Fixed OPEX	%/CAPEX	6	6

Tables 10 and 11 present the final costs for both absorption options. Table 10 shows the costs in unit €/t_{CO2} and Table 11 shows the answers in unit M€/a.

Table 10. CAPEX and OPEX for Amine and HPC Absorption

Amine		**CASE1**	**CASE2**
Capex	€/t_{CO2}	22.1	18.0
Opex variable	€/t_{CO2}	39.1	39.1
Opex fixed	€/t_{CO2}	16.5	13.4
TOTAL	€/t_{CO2}	77.8	70.5
HPC		**CASE1**	**CASE2**
Capex	€/t_{CO2}	19.9	16.2
Opex variable	€/t_{CO2}	24.1	24.1
Opex fixed	€/t_{CO2}	14.9	12.1
TOTAL	€/t_{CO2}	58.8	52.3

Table 11. CAPEX and OPEX for Amine and HPC Absorption

Amine		**CASE1**	**CASE2**
Capex	M€/a	8	13
Opex variable	M€/a	14.2	28.4
Opex fixed	M€/a	6	10
TOTAL	M€/a	28.2	51.2
HPC		**CASE1**	**CASE2**
Capex	M€/a	7.2	11.7
Opex variable	M€/a	8.7	17.5
Opex fixed	M€/a	5.4	8.8
TOTAL	M€/a	21.3	38.0

Figure 18 shows the final costs of amine and HPC absorption.

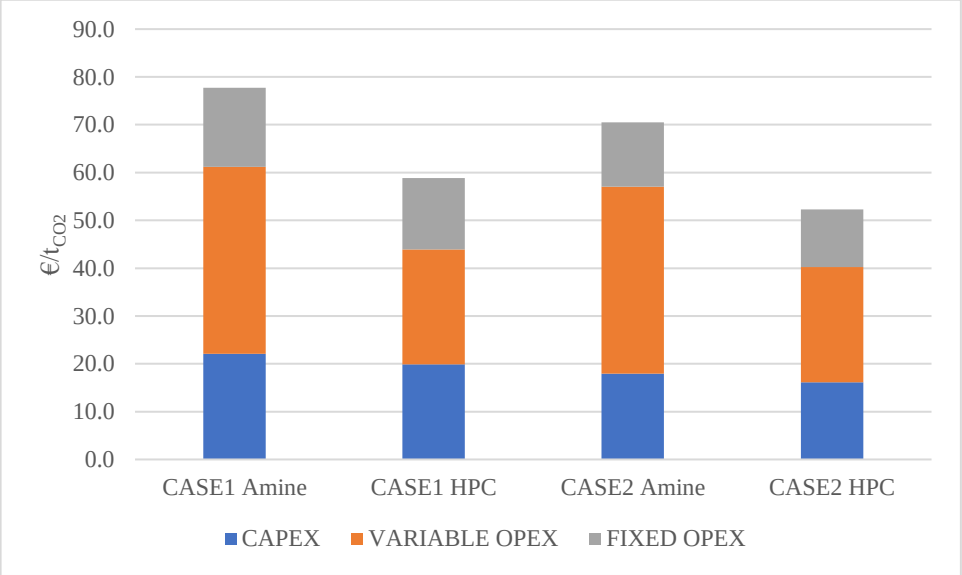

Figure 18. Amine and HPC Absorption Costs

Amine absorption costs 77.8 €/t_{CO2} in Case1 and 70.5 €/t_{CO2} in Case2. These values coincide closely with the gathered data. The data presented in the report "Teknologisten hiilinielujen mahdollisuudet ja niiden edistäminen Suomessa" (Kujanpää et al. 2023) align closely with the calculated values. The total cost of HPC absorption is 58.8 €/t_{CO2} in Case1 and 52.3 €/t_{CO2} in Case2.

Figure 18 shows that the costs are relatively lower for the larger power plant, partly due to the scaling advantage. This could make carbon capture more attractive for larger power plants. Costs are high, but so is the energy use of post-combustion capture. The energy consumption of CO_2 capture affects the energy consumption of the whole plant, reducing its overall efficiency. Many sources do not mention the boundaries of the system. Usually, the capture costs include treatment, compression, and intermediate storage. The correct price is affected by transportation and other handling.

Amine absorption is the most common separation method used for CO_2 separation, but other absorption techniques have also emerged such as HPC. The cost of HPC was calculated the same way as for amine absorption. The main difference between the techniques is that HPC consumes less energy for regeneration and thus most of the energy consumed is electricity. For example, the Bluenzyme technology patented by Saipem qualifies hot water for regeneration. (SAIPEM n.d.)

Unfortunately, investment costs for HPC are not available yet in public data, so the determination of investment costs is not based on the data found. The investment cost was estimated to be about 10 % lower due to:

- the vapor-free nature of the regeneration process
- easier drying of carbon dioxide
- the lack of water treatment for flue gases and
- the elimination of steam in the cooling cycle.

The calculations suggest that HPC is a cheaper option than amine absorption. However, amine absorption is better in separating CO_2 at low concentrations.

8.3 Discussion

The carbon capture utilization and storage market were estimated to be a combined 6.8 billion USD. However, carbon capture's investment and operating costs are still too high, so the commercial market for carbon capture will not generate investment. However, the carbon capture market is expected to grow to 17.3 billion USD by 2032, largely thanks to policy decisions. The emissions trading system influences the market, the price per ton of CO_2 emitted, and the price of CO_2 on the commodity/product market.

The price per ton of CO_2 traded is expected to drive investment in carbon capture, but the price per ton of CO_2 is still too low for this between 65 and 85 €/t_{CO2}. The projected price per ton of CO_2 would be stable at over 90 €/t_{CO2} around 2034, which would seem to be sufficient to provide an incentive for investment.

The energy and industrial processes sectors, which together account for around 63 % of CO_2 emissions, create the greatest demand for carbon capture. Many industrial processes still burn fossil fuels and will continue to do so. The switch to more sustainable processes has not been profitable yet, making carbon capture a necessary transitional tool.

The projections of the utilization of captured carbon range from very modest to quite high growth rates. Of the potential uses, bio-based synthetic fuel production has the highest potential. Another area with a high growth forecast is the chemical industry’s utilization.

There have been positive pilot project experiences recently, for example, Fortum's pilot project for using carbon dioxide to feed plastics. However, the growth of both sectors will be largely determined by policy decisions and must be monitored closely.

In utilization, the options are practically short-term storage, and it would be a better option to have longer storage. Technical carbon sinks can be formed by capturing biogenic CO_2. For example, it could become a good market opener for carbon capture in Finland. New biofuel plants with a long lifetime left and located close to good transport possibilities, all the forest industry plants could serve as sources for biogenic CO_2.

Of the capture technologies, the most commercially viable is post-combustion capture, which is already proven and relatively straightforward to link to an existing emission source. However, when considering the remaining lifetime of an existing plant. For this reason, CCS plants built after coal-fired plants will probably be located more in the so-called emerging countries, where new coal-fired power plants are still being built.

When considering new sectors and markets, it might be worth considering cooperation with players already familiar with the market. This would reduce risk-taking and allow for more knowledge sharing. It is also useful to compare the size of projects and plant investments with those that are known.

Calculations were made for the cost of carbon capture, amine absorption, and HPC absorption for power plants of different sizes. In both cases, the calculations include the capture itself as well as the treatment, compression, and intermediate storage of CO_2. The cost of amine absorption for a 200 MW plant was 77.8 €/t_{CO2} and for a 400 MW plant 70.5 €/t_{CO2}. Compare to the data found in Teknologisten hiilinielujen mahdollisuudet ja niiden edistäminen Suomessa" (Kujanpää et al. 2023) which was reported around 72 €/t_{CO2} for the 200 MW powerplant. From this source, the cost of carbon capture for a 400 MW powerplant was also calculated and it was around 64 €/t_{CO2} like the calculations.

The cost of hot potassium for a 200 MW plant is 58.8 €/t_{CO2} and for a 400 MW plant 52.3 €/t_{CO2}. HPC is therefore cheaper than amine absorption. However, it is difficult to verify the costs, as it is very difficult to find the investment and operating costs and to understand the calculations using only public data.

A customer survey shows that many companies see carbon capture as an interesting tool to mitigate climate change. However, the costs are still too high, so the implementation still requires support development, and particularly a reduction in costs.

Costs and lack of storage and further use are slowing down the growth of the carbon capture market. In Finland, for example, Neste abandoned a major carbon capture project. Also in Sweden, Vattenfall announced the termination of its carbon capture projects, mainly due to a lack of financing and the carbon dioxide market. Without these factors, CCS is not seen as a viable or attractive option. (Maula 2024; SVT Nyheter 2024)

Also in 2008, when Vattenfall invested in carbon capture from its coal-fired power plants in Germany (carbon capture was seen as a more realistic option than stopping coal combustion), the difficulty of finding a storage site and other problems shut the project down. (SVT Nyheter 2024)

It seems that investment in carbon capture will only really start when the price of carbon dioxide emissions is sufficiently high and when carbon dioxide usage or storage capacity increases significantly. The highest potential is in synthetic fuels, the size of which will be heavily influenced by future emissions trading in fossil fuel distribution.

There is much to support the prediction of strong growth in the carbon capture market over the next 10 years, as increased industrial production is expected to increase the emission price of carbon and its use as a commodity, thus making the market work. As a result, there will certainly be a need for players in the sector, both in terms of plant and equipment and process expertise.

Table 12. Summary of discussion

Category	Title
Market	Current carbon capture size $6.8 billion Expected to grow to $17.3 billion
Challenges	The price per ton of CO_2 is too low Lack of storage and utilization High costs
Key sectors for demand	Energy, industrial processes, and waste Synthetic fuel production Utilization in the chemical industry
Technology	Most viable: post-combustion capture Costs: Amine 66.7 €/t_{CO2} (200 MW) and 61.6 €/t_{CO2} (400 MW), HPC 48.9 €/t_{CO2} (200 MW) and 44.2 €/t_{CO2} (400 MW)
Customer Survey	Interest in carbon capture as a climate tool, high costs as a barrier
Future	Strong growth expected
Growth Drivers	CO_2 price projected to grow The industrial process demand, policy decisions

9 Conclusions

Greenhouse gas emissions remain in the atmosphere, preventing excess heat from escaping from the Earth and this causes global warming. Carbon dioxide is the most significant greenhouse gas, as its production volume is higher than other greenhouse gases. Therefore, the most effective way to reduce greenhouse gases in the atmosphere is to reduce carbon dioxide. Carbon capture is one possible tool to manage CO_2 emissions, especially for those sectors where replacing fossil energy emissions is challenging. Therefore, this thesis aims to investigate technologies for carbon capture and the market for carbon capture.

The thesis started with reviewing publicly available information on carbon emissions, particularly fossil emissions, i.e., a study of emissions trading. Emissions trading is one of the important existing political instruments, as carbon capture requires different drivers and legal conditions for its wider use. Other major drivers for carbon capture include increased environmental awareness and the potential utilization of carbon dioxide. However, the current drivers are insufficient to overcome the overall costs and immaturity of technologies for CCS and CCU, therefore legislation is needed.

Political acts help to promote and develop innovations. Tighter legislation for climate targets has already been implemented, which has encouraged the development of carbon capture. One driver to consider for carbon capture is an environmental permit policy that would oblige installations to include carbon capture in their processes. Policies could also influence the activation of carbon capture, for example through emissions trading.

Efforts should also be made to develop other forms of financing to make the marker work properly as this will create conditions for carbon capture. The EU has set up three funding bodies for carbon capture: the Innovation Fund, the Connecting Europe Facility, and Horizon Europe, which are intended to finance research and piloting in the field.

Global anthropogenic fossil emissions in 2022 were 38.5 Gt. In the same year 2022, EU CO_2 emissions were 2.9 Gt, and Finland's CO_2 emissions were 40 Mt. Such quantities show that, for example, to reach the Paris Climate Agreement there could be a demand for carbon capture.

Various methods and techniques have been developed to capture carbon dioxide. The methods related to combustion can be divided into three main categories: pre-combustion, post-combustion, and oxyfuel combustion capture. Many factors, including the source of carbon dioxide, concentration, existing/new plants, and processes influence the choice. In addition, all methods require pretreatment desulfurization. Pre-combustion and post-combustion capture also require nitrogen removal, oxyfuel combustion capture does not need it as it uses pure oxygen for combustion

Pre-combustion is best suited to IGCC power plants because they already have a combined cycle plant into which a separation unit can be easily added. Conversely, post-combustion can be built into existing combustion process plants with relatively minor modifications. Oxyfuel combustion is well suited for large industrial plants, oil refining, cement and lime industries, the steel industry, and new plants.

Pre-combustion and post-combustion capture are at level 9 at the technology readiness level while oxyfuel combustion capture is at level 7. This means that pre-combustion and post-combustion capture have been used commercially, while oxyfuel has been researched and piloted, but it is not yet commercially available.

Each of these methods has its processes and all have developed different separation techniques for the actual separation of carbon dioxide from gases. These techniques are absorption, adsorption, cold distillation, membrane separation, hydrate-based separation, and chemical looping. These separation techniques are in principle possible for all processes, but mainly the most appropriate one for the specific process is selected from several tested techniques.

After capture, carbon dioxide still needs to be further processed for treatment and intermediate storage and transported for utilization or long-term storage. Storage has been much discussed, especially in oil/natural gas-producing countries, but it requires high purity of CO_2. Whereas for utilization the CO_2 purity requirement depends on the application. Utilization is predicted to increase significantly as the production of synthetic e-fuels becomes profitable. Simultaneously, the need for biogenic CO_2 capture will increase, which is seen as a major opportunity in Finland, a country with a traditional forest industry.

This need and the rest of the carbon capture market were further investigated through a market study. It examined the current market, the potential, and the future of carbon capture.

The carbon market is said to have reached 4.4 billion USD in 2023 and is forecast to grow to USD 10.7 by 2032, depending largely on policy decisions. The greatest potential for carbon capture is in Europe and North America, where carbon capture is driven and supported. International cooperation can help to develop carbon capture technologies, expand knowledge, and lower prices, making carbon capture an even more attractive market option.

Although the market for carbon capture is not yet very large, emissions trading and the usage of CO_2 will eventually lead to a real opening in the market. Carbon capture seems to be a very potential option, especially for sectors where there are challenges to reducing carbon dioxide emissions, such as the energy industry, industrial processes, and waste incineration sectors.

The main problems with capture are not the price per ton captured but the lack of storage capacity and the lack of market for CO_2. The location of the capture plant impacts the profitability of carbon capture. The plants must be close to good transport facilities or close to the end users of CO_2.

Carbon capture is a promising way to reduce the impact of climate change. Its success depends largely on technological development, cost reductions, and legislative support. The technology market is still at an early stage, with significant economic opportunities. The new markets and jobs that capture can create play a major role in supporting sustainable economic growth. Carbon capture is an important tool for managing climate change, but it is only a part of a wider solution.

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Appendix 1. Customer survey questions

1

Onko hiilidioksidin talteenotto ja sen mahdollisuudet teille ennestään tuttua?*

2

Näettekö hiilidioksidin talteenoton realistisena ratkaisuna ilmastonmuutoksen hillitsemisessä?*

Valitse yksi tai useampi vastaus

- [x] Kyllä
- [ ] Ei

3

Mitä haasteita tai esteitä näette hiilidioksidin talteenoton käytössä teollisuutenne alalla?*

Esimerkiksi kustannukset, energiankulutus, sääntely ja politiikka yms.

4

Kokisitteko hiilidioksidin talteenoton houkuttelevampana vaihtoehtona, jos hiilidioksidin talteenoteton lisäksi olisi olemassa mahdollisuuksia talteenotetun hiilidioksidin jatkojalostukseen tai varastointiin?*

Esimerkiksi synteettinen polttoaine tai meren pohjaan pumppaaminen

5

Millaisia tukia / kannustimia hallitukselta tai muilta tahoilta näkisitte tarpeellisina, jotta talteenotto olisi taloudellisesti kannattavaa yrityksellenne?*

6

Oletteko investoineet tai harkitsetteko investointeja hiilidioksidin talteenottoon? Jos kyllä, millaisia teknologioita pidätte lupaavimpina?*

7

Minkälaisella aikataululla yrityksenne voisi harkita hiilidioksidin talteenottoa?*

8

Näettekö, että Suomessa olisi käytössä laajemmassa mittakaavassa hiilidioksiidin talteenottoa 2030 tai 2040 mennessä?*

9

Onko asiakkaidenne tai kumppaneiden joukossa kiinnostusta hiilidioksidin talteenottoon?*

10

Näettekö hiilidioksiin talteenoton strategisena etuna verrattuna kilpaileviin yrityksiin?*

English

1. Are you familiar with carbon capture and its potential?
2. Do you see carbon capture as a realistic solution to mitigate climate change
    a. Yes
    b. No
3. What challenges or barriers do you see in the use of carbon capture in your industry?
    a. For example, cost, energy consumption, regulation, and policy, etc.
4. Would you find carbon capture a more attractive option if, in addition to capture, there were possibilities for further processing or storage of the captured carbon?
    a. For example, synthetic fuel or pumping to the bottom of the sea.
5. What kind of support/incentives from the government or other bodies would you consider necessary to make recovery economically viable for your company?
6. Have you invested or are you considering investing in carbon capture? If yes, which technologies do you consider most promising?
7. What is the timeframe for your company to consider carbon capture?
8. Do you see carbon capture being deployed on a larger scale in Finland by 2030 or 2040?
9. Is there interest among your customers or partners in carbon capture?
10. Do you see carbon capture as a strategic advantage over competing companies?