FACULTY OF TECHNOLOGY

FLEXIBLE CARBON CAPTURE IN NORDIC ENVIRONMENT

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ABSTRACT

Flexible carbon capture in Nordic environment

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The escalating levels of atmospheric carbon dioxide (CO_2) from fossil fuel emissions demand urgent climate action. Carbon capture (CC) stands as a critical technology for mitigating climate change impacts. This thesis conducts a comprehensive literature review focusing on flexible CC possibilities in the Nordic context.

The study explores various carbon capture technologies, emphasizing their potential for flexibility in application. Absorption, adsorption, membrane, chemical looping, and cryogenic methods are examined, elucidating their mechanisms, energy requirements, and suitability.

Flexible CC facilities can be used as dynamic solutions for balancing energy supply and demand, particularly in regions with fluctuating needs like the Nordics. Integration of post-combustion carbon capture units into power plants emerges as an adaptable approach, allowing for independent installation and improved profitability.

Moreover, the research investigates the implications of flexible CC on CO_2 emissions reduction and grid stability, particularly during peak demand periods. By leveraging excess clean energy during low-demand periods, flexible CC facilities can effectively capture CO_2, contributing to climate change mitigation efforts.

Challenges such as high initial investment costs, regulatory barriers, and scalability issues persist. The study underscores the need for further research into the economics, utilizatio transportation, and scalability of CC projects to realize their full potential in combating climate change.

Keywords: Carbon, Capture, Flexible

Joustava hiilen talteenotto pohjoisessa ympäristössä

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Opinnäytetyö käsittelee hiilidioksidin talteenottoa ja hyödyntämistä Pohjoismaisessa kontekstissa tavoitteenaan puuttua nouseviin ilmakehän hiilidioksiditasoihin. Tutkimus suorittaa kirjallisuuskatsauksen erilaisiin hiilen talteenotto teknologioihin keskittyen niiden joustavuuteen ja sovellettavuuteen. Keskeisiä teknologioita kuten absorptiota, adsorptiota, kalvoerotusta, kemiallista silmukointia ja kryogeenisiä menetelmiä tutkitaan, korostaen niiden mekanismeja, energiavaatimuksia ja soveltuvuutta.

Tutkimus korostaa joustavien hiilen talteenottolaitosten merkitystä energian tarjonnan ja kysynnän tasapainottamisessa, erityisesti alueilla, joilla energia tarpeet vaihtelevat, kuten Pohjoismaissa. Post-combustion CO_2 talteenottoyksiköiden integrointia voimalaitoksiin esitetään joustavana ratkaisuna, tarjoten itsenäisen asennuksen ja parannetun kannattavuuden.

Lisäksi tutkimus tarkastelee joustavien hiilen talteenottolaitosten vaikutuksia hiilidioksidipäästöjen vähentämiseen ja verkon vakauttamiseen, erityisesti huippukysyntäaikoina. Hyödyntämällä ylimääräistä puhdasta energiaa alhaisen kysynnän aikoina, joustavat hiilen talteenottolaitokset voivat tehokkaasti ottaa talteen hiilidioksidia edistäen siten ilmastonmuutoksen torjuntatoimia.

Mahdollisten hyödyt ollessa suuret, on olemassa myös haasteita, kuten korkeita alkuinvestointikustannuksia, sääntelyesteitä ja skaalautumisongelmia. Opinnäytetyö korostaa tarvetta edelleen tutkimukselle hiilen talteenottoprojektien taloudellisuudesta, CO_2:n hyödyntämisestä, kuljetuksesta ja skaalautuvuudesta niiden täyden potentiaalin hyödyntämiseksi ilmastonmuutoksen torjunnassa.

Avainsanat: Hiili, Talteenotto, Joustava

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LIST OF ABBREVIATIONS

BECCS	Bioenergy carbon capture and storage
CC	Carbon Capture
CCU	Carbon Capture and Utilisation
CCUS	carbon capture utilization and storage
CDR	Carbon Capture Removal
CLC	Chemical looping combustion
CO_2	carbon dioxide
COP26	Climate Change Conference in Glasgow 2021
DAC	Direct air capture
EU	European Union
GHG	Greenhouse gas
Gt	Gigaton
IEF	International Energy Forum
IPCC	Intergovernmental panel on climate change
MEA	monoethanolamine
Mt	Megaton
NETP	Negative emissions and practices
NG	Natural gas
USA	United States of America
C°	Temperature (Celsius)

1 INTRODUCTION

Atmospheric carbon dioxide (CO_2) sourced from fossil fuels has been increasing drastically since the last century (Figure 1). CO_2 happens to be the largest greenhouse gas (GHG) on planet earth. (NOAA 2024). To limit the climate warming to 1.5 Celsius (C°) we need to make many changes to the way production and consumption are thought. Carbon dioxide removal (CDR) is one of these important technologies that can be a gamechanger in the coming decades.

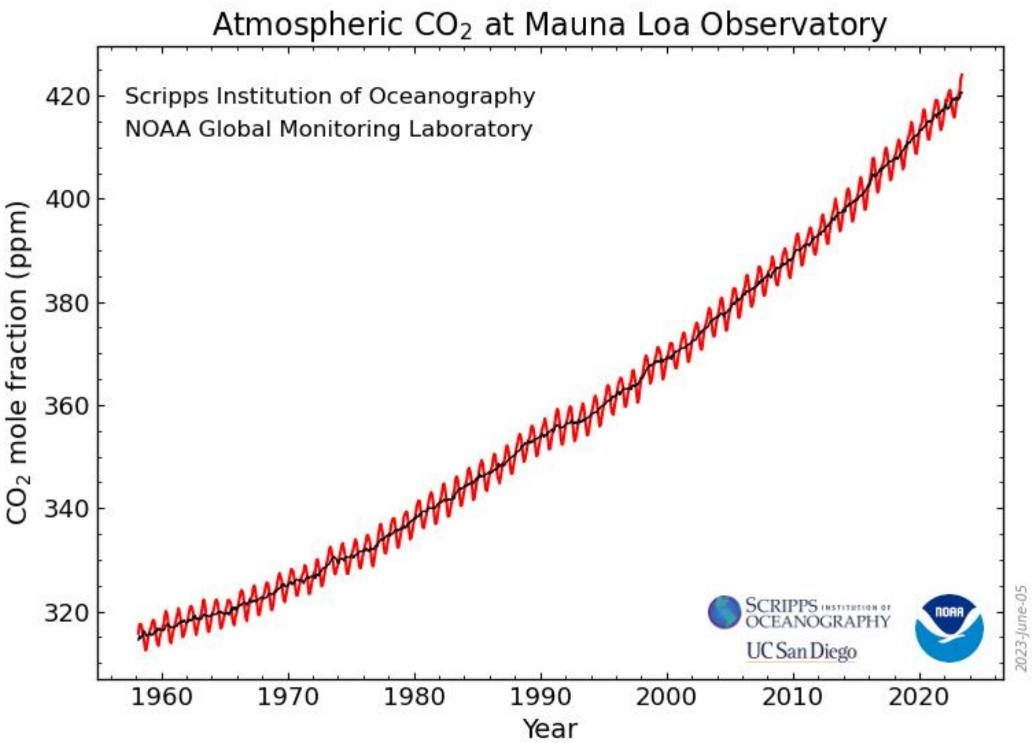

Figure 1. This graph shows atmospheric CO_2 levels measured from United States of America (USA) Hawaii Mauna Loa Observatory from 1958 to 2023. (Lindsey, 2024)

Carbon capture utilization and storage (CCUS) will have to grow by 120 times by 2050 to meet with the net-zero commitments agreed in UN Climate Change Conference held in Glasgow 2021 (COP26)(McKinsey).

Carbon capture can be divided into technological and natural carbon capture. In this thesis I will mainly focus on CC technologies. This thesis is a literature review and will study the possibilities of flexible carbon capture in Nordic environment as a solution to reduce CO_2

emissions from atmosphere. This thesis will also introduce some of the utilisation possibilities of the captured carbon. The goal of this thesis is to answer the following research question: What are the possibilities of flexible carbon capture and utilization in Nordic environment? The main underlying interest is to review the availabe CC technologies and their flexibilities in terms of energy demand. This, in turn, would represent a potential partial solution to balance the energy system ever more dependent to variable renewable resources.

There are many publications and research on CCUS, but technologies are advancing at fast rate due to political pressure and increasing funding. In 2023 we have seen huge investments on carbon capture plants for example US government funding CC with up to $2.5billion dollars (Wu, 2023).We have also seen huge investments from one of the biggest private equity companies in the world as Blackrock invested $500 million dollars into direct air capture company (Bentley, 2023). As we get more investments in the sector, we will hopefully see new innovations and research regarding CCUS.

The structure of this study is as follows. First, we discuss CC in general, including climate change mitigation and economics of CC. In the third chapter, we overview some of the common CC technologies. In the fourth chapter we focus on utilization of the captured carbon. In chapter five we process the possibilities of flexible CC. In chapter five, we present the conclusions and recommendations.

2 CARBON CAPTURE

2.1 Climate change mitigation and carbon capture

According to Intergovernmental Panel on Climate Change (IPCC) anthropogenic GHG emissions needs to be at net zero level by 2050 to meet 1.5C° limit agreed in Paris 2015 for climate warming. (Fawzy et al., 2020). CCUS and bioenergy carbon capture and storage (BECCS) and are very potential tools of technology to mitigate the climate change. Many of the published strategies see them as a crucial part to lower our CO_2 emissions to the agreed level. 275 scenarios on climate change mitigation estimates on average, that negative emissions and practices (NETP) needs to total 11.940 $MtCO_2$/yr. in 2050 and 27.950 $MtCO_2$/yr. in 2100 (Table 1). These scenarios are calculated to meet the global warming limit of 1.5 C°. (Koljonen et la., 2021).

Table 1. This table shows median value of NETPs ($MtCO_2$/yr.) in 2050 and 2100. This table is created using data from (Koljonen et al.,2020)

NETP	Number of scenarios	Median value in 2050, $MtCO_2$/yr	Median value in 2100, $MtCO_2$/yr
BECS	266	3300	10840
DAC-CCS	8	50	6420
Afforestation	51	3790	4740
Enhanced weathering	1	1200	2500
Biochar	1	3600	3500
Total NETPs	275	11940	27950

2.2 Natural carbon capture

Carbon capture can happen in many ways. In nature, carbon capture happens for example in form of growing trees. While a tree is growing, it is using CO_2 from the air to create photosynthesis (National Geography Society, 2024) This process captures carbon into the tree or a plant as a form of biomass. After some time, the tree or a plant starts to decay and release the captured carbon back into the atmosphere. This cycle is carbon neutral because all the captured carbon will eventually wind back to the cycle. What if we could prolong this process or even stop the carbon returning to the cycle? In that case the process would not just be carbon neutral. That is the primary goal of carbon capture, remove the CO_2 from the atmosphere permanently and, potentially, using it for something useful or store it somewhere .

The two most important ways of natural carbon capture are biomass growth and CO_2 dissolution into oceans. When CO_2 dissolves into the ocean, it reacts chemically with water and carbonate ion molecules forming eventually bicarbonate acid, which is bad for the biodiversity of oceans. (NOAA, 2020)

Reforestation and afforestation are very viable ways to reduce atmospheric CO_2. Forests are a central part of climate change mitigation. Planting trees in some of the old forest areas can make a significant impact on climate, biodiversity, and number of other factors (Sappi Global). Afforestation of grassland, savannas and peatlands is listed as high confidence in IPCC 2022 summary for policymakers. (IPCC, 2023). This thesis will focus on technological CC.

2.3 Technological carbon capture

With CC technologies we can capture CO_2 straight from air we are breathing anywhere in the world. These methods are called Direct Air Capture (DAC). This technology can be deployed anywhere in the world. World largest DAC facility is in Iceland (figure 2). This facility uses energy from a nearby geothermal powerplant to extract about 4,000 tons of CO_2 /Yr. This facility is also the first large-scale carbon dioxide removal plant (Reuters, 2021). The cost of captured carbon by DAC technologies are fairly high due to low CO_2 density. (Karimi et al., 2023).

Early studies show that DAC facilities can be used flexibly with excess electricity, however the energy mix needs to be 80% originated from renewable sources. (Mikulčić et al., 2019a). DAC facilities mainly use adsorption and absorption as a method to separate CO_2 from the air. (Fawzy et al., 2020)

Figure 2. This figure shows the world's largest DAC facility in operation. This CC plant locates in Iceland. (Reuters, 2021.)

With point source CC technologies, we can capture CO_2 before or after the oxidation of the carbon. These methods are called pre combustion carbon capture and post combustion carbon capture. (Kujanpää et al., 2023.)

CO_2 capture via post-combustion technologies is basically removing CO_2 from the flue gases after the oxidation process in the CC unit. After carbon dioxide is removed, mostly carbon dioxide free emission gas is freed into the atmosphere (Karimi et al., 2023). This technology has higher efficiency for energy usage compared to pre combustion technologies. Post-combustion technologies can also be installed to existing power plants more easily. This leads to cheaper equity investments. (Krishnaiah et al., 2014)

Post combustion technologies can be used flexibly. Two generally known and used ways to flexibly separate CO_2 from flue gas, are bypass and venting systems. With these systems flue gases can bypass CO_2 separation unit entirely and activated when there is excess electricity. (Mikulčić et al., 2019)

In pre-combustion CO_2 capture, carbon is removed from the fuel before oxidation process. This method is mostly used in natural gas, biogas, and synthetic gas. Pre-combustion CC can be used to produce hydrogen. (Karimi et al., 2023).

Most noticeable challenge of the pre combustion technologies is that it needs complicated chemical processes before the turbine. This can lead to lower efficiency of the power plant.(Krishnaiah et al., 2014)

2.4 Challenges of carbon capture

Current challenges with CC technologies are the high cost of the energy intensive process, especially with DAC technologies. Another remarkable problem is the scalability of the process.

CC plants are very expensive and require large investments. Furthermore, the regulatory process for CC plants is ineffective. According to the International Energy Forum (IEF), there is a lack of public acceptance due to safety concerns. Boosting CC plant production requires grater support from governments and regulatory organs like the European Union (EU). (IEF)

Captured carbon needs to be utilized and stored. This is said to be the backbone of the carbon management industry. Higher storage capacity will affect the market conditions of CC positively. (IEA, 2023.). CO_2 needs to be transported from its capture plant to the storage or utilization site, which is quite expensive at large scale. Current transportation techniques are quite similar to natural gas for example. CO_2 can be transported by pipeline, ships, trucks, and rail. For large quantities of CO_2, the best transportation options are by ship and pipeline. (Global CCS Institute)

3 COMMON CARBON CAPTURE TECHNOLOGIES

CO_2 technologies can be divided into five major branches (figure 3). In this chapter we will go through the main technologies to separate carbon dioxide.

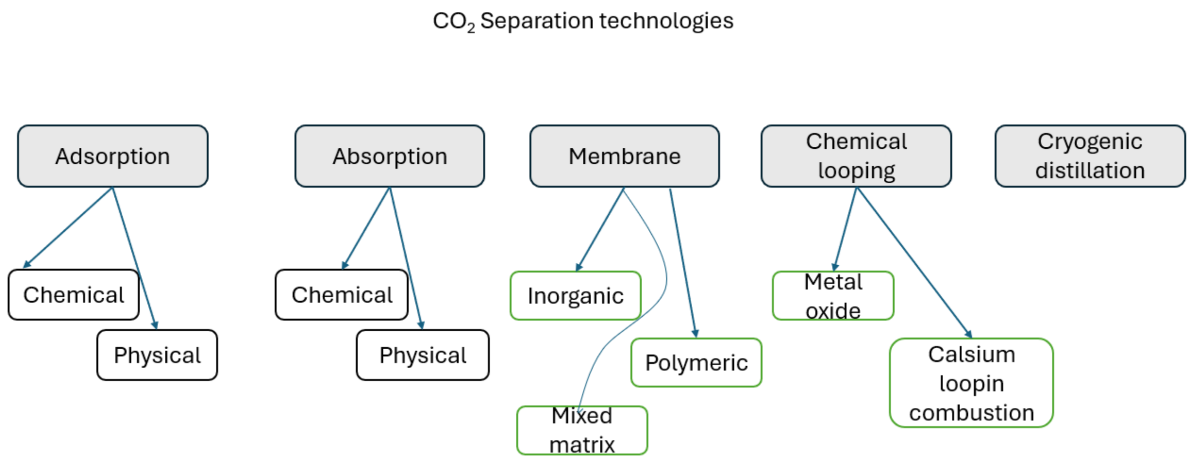

Figure 3. This figure displays five main branches of CO_2 separation technologies. This image was created using information from (Karimi et al., 2023).

3.1 Adsorption

Carbon dioxide separation process from multiple component stream by adsorption is executed using a solid surface. This method is based on intermolecular forces between the gases of the stream and adsorbent material. CO_2 separation by absorption can be divided into two categories: physical and chemical adsorption. Materials used as absorbent varies between these categories. In physical adsorption physical qualities matter more, like pore size and surface design including its texture is a key factor on its adsorption abilities. Chemical adsorption uses metallic materials that have been treated/coated in salts or different oxides to activate it. (Karimi et al., 2023; Krishnaiah et al., 2014)

This adsorption process is executed in packed column, where CO_2 containing gas stream flows through absorbent material. After an absorbent material has absorbed enough CO_2, it needs to be regenerated and can be used again. (Krishnaiah et al., 2014)

CO_2 removal by adsorption process has relatively low energy consumption due to its exothermic features. This process is able to remove up to 95 % (Karimi et al., 2023) of the CO_2 in the stream. This technology has been listed as a potential post-combustion process mainly because of its low energy requirement. (Krishnaiah et al., 2014)

3.2 Absortion

Absorption is separation technology which is used to separate certain elements from the gas stream. This separation process is done in a different type of columns, like packed column and plate column.(Muurinen Esa, 2023) Absorbents can be divided into two groups by the way they absorb the component. These groups are chemical absorption and physical absorption. Chemical methods require chemical reaction while the absorption happens. Physical method is based on mass transfer in the interface are of the surfaces.(Krishnaiah et al., 2014)

In plate column for example, gas stream and liquid absorbent are flowing in opposite direction inside the column. In this process absorber component (liquid) absorbs wanted component from the gas stream (Muurinen Esa, 2023).

Separated component can be the one that is transferred to the liquid or the one remaining in gas stream. When absorption is happened, the absorbent needs to be regenerated. This process can be done many ways, for example in stripper or in distillation column.(Muurinen Esa, 2023)

Absorbents have been studied and tested to find the most suitable option. One class of absorbents for separation process is aqueous monoethanolamine (MEA). It is used to separate CO_2 in low concentration conditions and is suitable for post combustion CC appliances.(Singh et al., 2022). This technology is commercially active and the approximated cost of CO_2 capture using MEA-absorption is 55 USD/ton and the corresponding energy consumption is 4 MJ per captured kg of CO_2.(Song et al., 2019)

With absorption technologies it is possible to remove about 90% of the CO_2 in the gas stream. There are few problems this type of technology faces; absorption process is quite energy intensive and absorbent liquid can cause corrosion. Amine based solvents have also been reported to decompose and form toxic gases (Bui et al., 2018; Krishnaiah et al., 2014)

3.3 Chemical looping

The chemical looping method is dating back to the early 1900's. In all its simplicity chemical looping is a process where an oxygen carrier, usually metal oxide, transfers oxygen into the process stream. One very potential CC technique called chemical looping combustion (CLC) uses this method to transfer oxygen. (Fawzy et al., 2020)

CLC is an innovative technology where solid particles transport oxygen from oxidation air to the oxidative product. This system uses two reactors, a fuel reactor and an air reactor. (figure 4). When combustion happens in the fuel reactor and in the air reactor, the metal oxide is regenerated. Metal oxides carry oxygen into the fuel reactor and releases its content to oxidize the fuel. As the oxidation happens without straight contact with air flue gases leaving from the fuel reactor are mainly CO_2 and H_2O. Flue gases needs to be dryed and compressed. Then it is ready for transportation and utilization (Mikulčić et al., 2019a)(Czakiert et al., 2022).

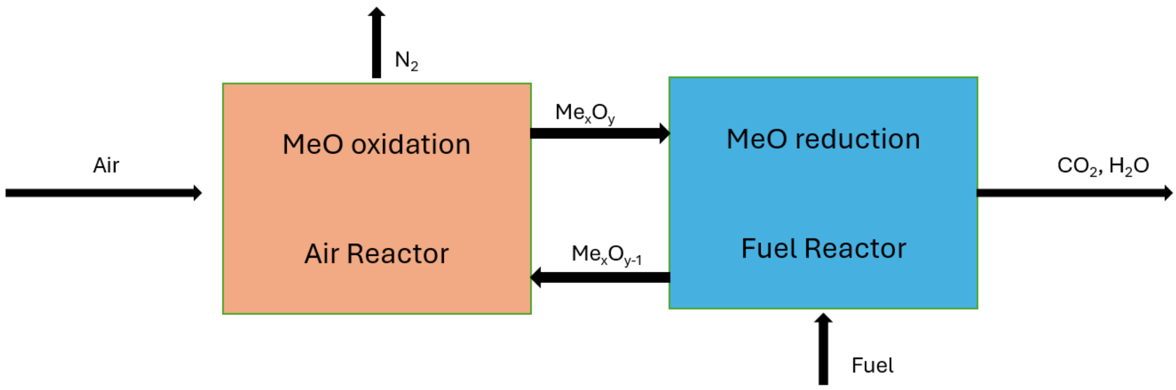

Figure 4. Chemical looping combustion system. Image recreated from (Czakiert et al., 2022).

However, this technology is not yet commercially viable, but studies show it can provide capture percentage of CO_2 over 90% (Czakiert et al., 2022).

3.4 Membrane gas separation

Membrane technology is a very viable way to separate CO_2 from the flue gas stream. Membrane technology has been used to strip natural gas (NG) from excess CO_2 to meet standards. (Khalilpour et al., 2015)

The bacic principle of membrane gas separation is shown in figure 5. Feed mixture spits in two, retentate and permeate. Retentate is the part of the gas which does not go through the membrane and the permeate is the part of the gas stream that penetrates the membrane. (Muurinen Esa, 2023)

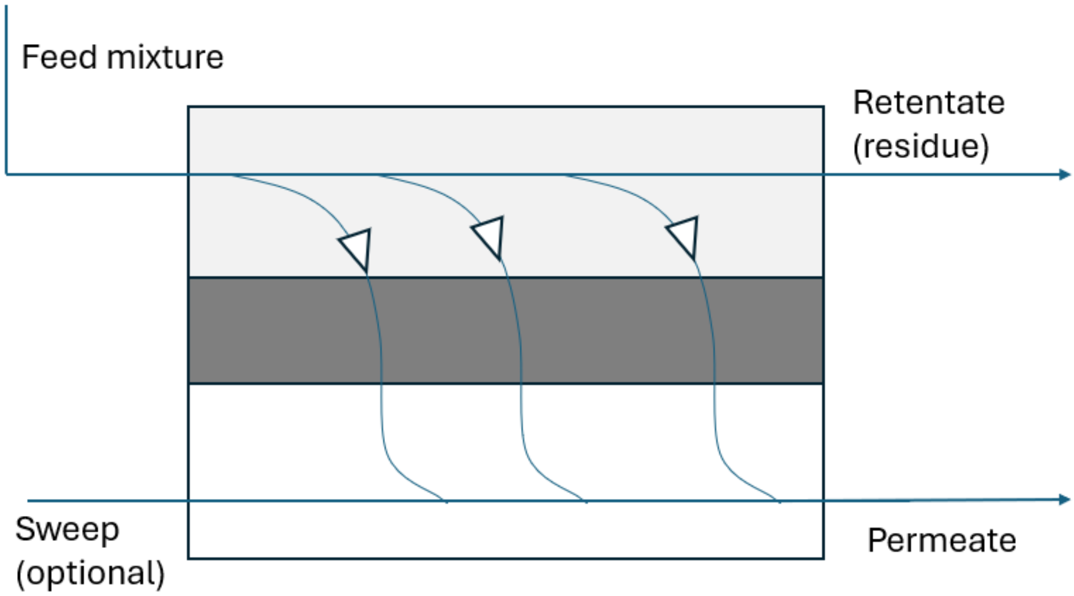

Figure 5. Basic principle of membrane gas separation. Image produced from (Muurinen Esa, 2023)

There are three types of membranes in use, polymer membranes, inorganic membranes, and mixed matrix membranes. Early membranes were made of nature polymers like cellulose and rubber. Modern polymer membranes are synthetic materials. Inorganic membranes are being researched. These could be made from ceramic or zeolite. (Mikulčić et al., 2019). Mixed matrix membranes are polymeric membranes filled with inorganic particles. (Khalilpour et al., 2015).

Membrane gas separation technology is often used in a hybrid system with another separation method like amine scrubbing (absorption) and cryogenic distillation. It is also used as a standalone post combustion CC system where are more than one membrane to ensure needed purity of CO_2 (Song et al., 2019).

Problems with this technology are its concentration requirements and swelling of the membrane. Membrane separation is only usable technology when CO_2 concentration is over 10% and economically productive in concentration of 20% and over. This is explained due the lower partial pressure, which is connected to the efficiency of the process. High temperatures and pressures can cause the membrane to swell. This will lead to lower selectivity and permeability for every gas in the stream.(Khalilpour et al., 2015; Mikulčić et al., 2019).

Industrial use of membrane is not practical due to its tendency to not tolerate high temperatures (over 100 C°) of the flue gas. Membranes are also sensitive for corrosive gases like SO_x NO_x and H_2S and needs pretreatment if some of these gases are included in the stream. (Song et al., 2019)

Benefits of this technology are its simplicity, environmental friendliness, and its energy efficiency (Song et al., 2019). Single stage membrane separation process consumes 2-6 MJ/ captured kg of CO_2. (Song et al., 2019)

3.5 Cryogenic carbon capture

Cryogenic carbon capture is based on condensation and desublimation features of the flue gas. This is very competitive CO_2 separation technology in industrial sector if there is possibility to use leftover cold energy from the process side streams. (Mikulčić et al., 2019b; Song et al., 2019).

With cryogenic technologies we can separate CO_2 from the flue gas with very high recovery and purity rates up to 99.99%. This is much higher than any other separation technology (Song et al., 2019).

There are plenty of different cryogenic technologies to separate CO_2 flue gas, but in this study, we will discuss about cryogenic distillation. Distillation in general is one of the best-known separation method of all time. Figure 6 shows cryogenic distillation using Ryan Holmes method (O'Brien, 1983). In this process feed stream is precooled and chilled afterwards using heat exchanger. Then gas stream is led to the distillation column, where the separation happens, and gas stream is divided into bottom and top products. CO_2 condenses into the bottom product and is heated and purified in the separator. (Song et al., 2019)

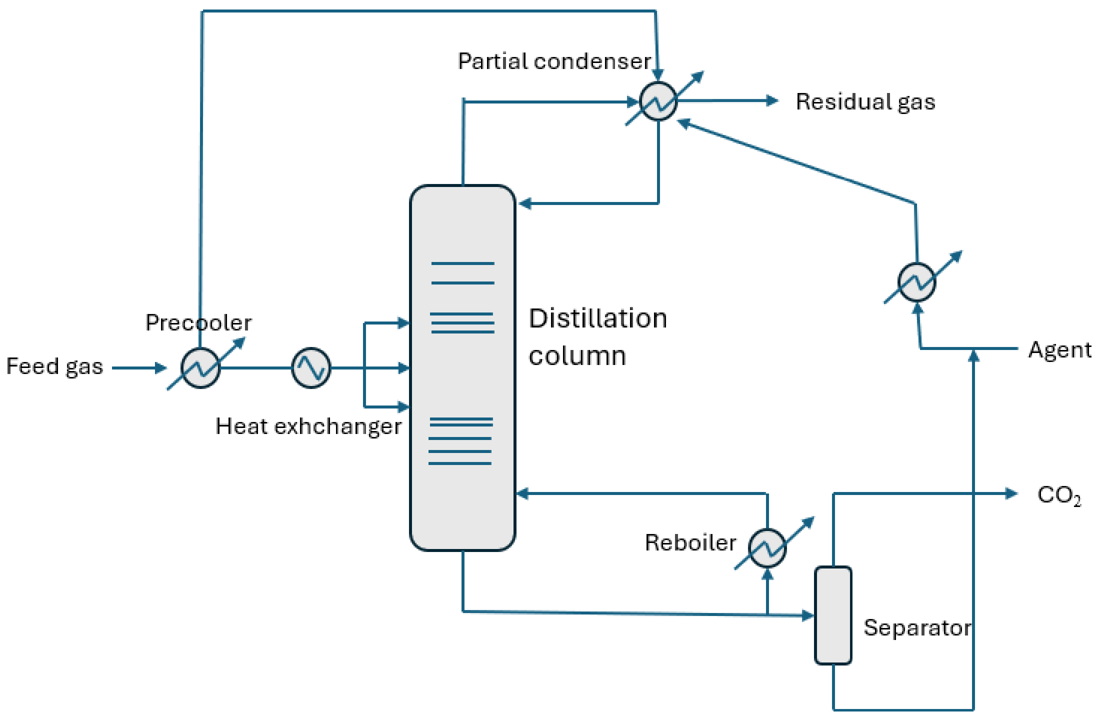

Figure 6. Cryogenic distillation process with Ryan Holmes method. Image recreated using (Song et al., 2019).

Cryogenic distillation is a very energy intensive process and energy demand can be over 50% of the facility's running cost. There have been studies that suggest it is reasonable to use cryogenic distillation as a part of hybrid post combustion carbon capture plant. One very promising hybrid system uses membrane technology alongside cryogenic distillation. In this type of process, energy consumption is much lower than standalone cryogenic process. Energy consumption in hybrid system is approximately 2-4 MJ/captured kg of CO_2. Standalone cryogenic CC plant uses up to 12 MJ/captured kg of CO_2 depending on plants size (Song et al., 2019). Cryogenic CC system can be used as a cold storage (Mikulčić et al., 2019a).

4 POSSIBILITIES OF FLEXIBLE CARBON CAPTURE IN NORDIC ENVIRONMENT

4.1 Energy production in Nordic environment

Energy demand is growing worldwide. Countries and companies are moving away from fossil fuels and electricity from renewable sources is very viable option. This process is called electrification (Department of Energy) A good example is the electrification of the transport sector. Modern trains use electricity and during this century electric cars have become widespread. (Tamor & Stechel, 2022)

The corresponding green transition of electricity production is seen in the graph shown in figure 7. There can be noticed that the use of fossil fuels has decreased notably and electricity production using renewable sources like wind has increased.

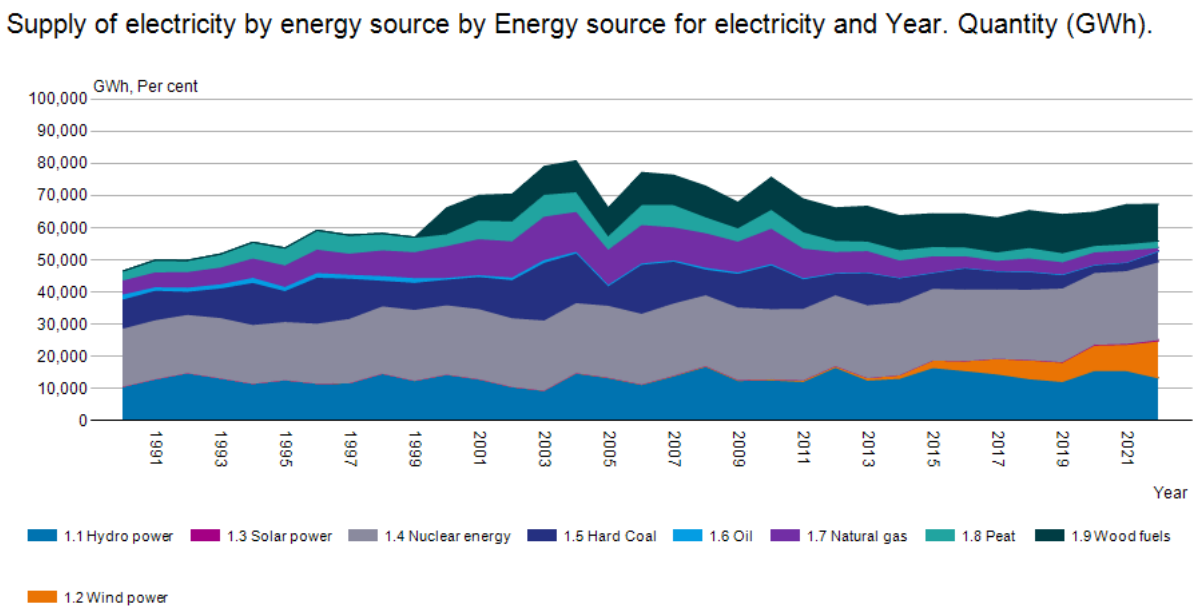

Figure 7. Finland’s electricity consumption by sector from 1990 to 2022.(Statistics Finland PxWeb,

https://pxdata.stat.fi/PxWeb/pxweb/en/StatFin/StatFin__ehk/statfin_ehk_pxt_12vp.px/chart/chartViewAreaStacked/)

Nordic countries like Finland have the peak electricity consumption and production during wintertime. The geographical location of Nordic countries ensures cold weather during winters and thus electricity consumption is high due to heating of living spaces. (Jaaskelainen et al., 2017)

During summertime there has been a challenge with overproduction of electricity in Finland. Sunny and windy days may lead to overproduction when electricity consumption is lower. There have been cases where renewable electricity production by windmills and solar farms has been halted due to overproduction. (Hamilo, 2012.)

4.2 FLEXIBLE USE OF CARBON CAPTURE

As mentioned before, CC facilities can be energy intensive due to process requirements. Therefore, flexible use of these facilities is much needed. Flexible CC facilities are potentially a very viable solutions to be used as a balancing factor between supply and demand and stabilize power grid during moments of high supply and low demand and vice versa. CC units integrated in powerplants can be bypassed or vented to activated or deactivate carbon capture unit flexibly. The two most studied technologies are using post-combustion and pre-combustion technologies (Mikulčić et al., 2019a). Post-combustion facilities are suitable for flexible use because it is independent of the power system. (Cohen et al., 2010)

A study by Stuart M. Cohen shows that flexible CC power plant can reduce CO_2 emissions and improve profitability by 10% compared to inflexible capture. (Cohen et al., 2010)

Table 2 shows data about ramp-up times of different CC technologies in flexible carbon capture facilities. Low ramp-up times are an upside aspect for flexible CC facility but there are also other factors that need to be considered regarding flexible CC facility. Table 2 shows all technologies addressed in this study except cryogenic technologies. That is because I had difficulties finding information for that technology. Cryogenic technologies are often used together with other separation methods.

Table 2. Ramp up times for different CC technologies.

Separation technology	Ramp-up time	reference
Absorption (packed column)	1 h	(Brouwer et al., 2013)
Membrane	¼ h	(Yuan et al., 2019)
Adsorption	8 min	(Wilkes & Brown, 2022)
Chemical looping	4 h	(Schnellmann et al., 2018)

5 CONCLUSIONS AND RECOMMENDATIONS

In this study we performed literature review about most common carbon capture technologies known today and their flexible use in Nordic environment. The results are that post-combustion carbon capture units can be very flexibly while integrated into power plants. Post-combustion CC unit can be installed as an independent part of the power plant unlike pre-combustion CC plant. This lowers the required capital investment and increases profitability.

We reviewed and studied basic mechanism for five separation methods, absorption, adsorption, membrane, chemical looping, and cryogenic distillation. Each separation method has different qualities, and they are used in different conditions. Purity of the product (CO_2) is also important factor for the separation process. There are also differences in energy consumption between these five separation process. If CC plant integration cite has excess cold energy, then best solution might be cryogenic CC system.

Flexible post-combustion facilities use venting and bypassing systems to guide flue gases into the CC unit or into the atmosphere. Flexible CC facility has improved profitability compared to the inflexible CC facility.

In Nordic environment, electricity consumption peaks in cold winter months due to heating of homes and other living spaces. While electricity consumption sets lower in summer months, the electricity infrastructure can over produce electricity, and windmills and solar farms needs to be halted. Flexible CC is energy intensive, and it can be ramped up in under 10 minutes, depending on technology used.

There is lots of potential for flexible CC in Nordic countries. Especially using post-combustion CC integrated to the existing powerplants, supporting clean electricity production to reduce anthropogenic CO_2. Furthermore, CO_2 could be utilized in other products or used as it is.

Carbon capture is important tool to reduce atmospheric CO_2 and needs to be studied further. This thesis did not review the utilization or transportation of captured carbon. Furthermore, in this thesis we did not study the economics of CC projects. These are also very important aspects of CC and need to be researched. Scalability of Carbon capture is also a challenge.

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